Title: The relationships between selected physical qualities, fast bowling kinematics, and cricket fast bowling performance

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ABSTRACT

Although strength and conditioning of cricket fast bowlers has become more specialized in recent times, little is understood about the interplay between physical capacities, fast bowling kinematics, and fast bowling performance measures. This study sought to determine these interrelationships. Thirty-one male amateur fast bowlers completed three test sessions on separate occasions 4–7 days apart. The first testing session comprised an eight-over fast bowling assessment, where performance and selected bowling kinematics were measured. A physical test battery was completed over the remaining two sessions. Peak and mean ball release speed were related with 1RM pull-up strength ($r_s = 0.56, p = 0.005$) and correlated with 20-m sprint time ($r_s = -0.42, p = 0.022; r_s = -0.37, p = 0.044$, respectively). Mean radial error was associated with 10-m and 20-m sprint times ($r_s = 0.41, p = 0.030; r_s = 0.38, p = 0.037$, respectively), and correlated with height and peak power from three countermovement jumps ($r_s = -0.39, p = 0.036; r_s = -0.41, p = 0.031$, respectively), and mean peak power from 20 countermovement jumps ($r_s = -0.45, p = 0.020$). Bivariate variable error was correlated with front-leg extension angle at ball release ($r_s = 0.41, p = 0.036$), and also with approach speed ($r_s = -0.36, p = 0.050$). These relationships may assist strength and conditioning coaches in designing more effective training interventions to enhance bowling speed and accuracy. Training interventions are warranted, however, to validate these associations.

KEYWORDS

Strength; Power; Power-Endurance; Acceleration Speed; Bowling Speed; Bowling Accuracy.
INTRODUCTION

Fast bowling is an important and exciting element to the international game of cricket. Fast bowlers represent the majority of the ‘bowling attack’ against opposition batsmen. They are typically required to bowl fast, accurate, and consistent throughout a bowling spell (series of six deliveries per over for multiple overs) or repeated spells (33), in attempt to dismiss opposition batsmen. Unfortunately, fast bowlers are at greatest risk of injury compared to batsmen, wicket-keepers, and spin bowlers (38). Poor physical preparation, along with unsafe bowling technique and minimal or excessive bowling workload is likely to predispose a fast bowler to injury (7).

Strength and conditioning of elite and sub-elite fast bowlers has become more specialized in the past two decades, in the quest to enhance fast bowling performance. Elite fast bowlers believe it is necessary to possess athleticism, strength, speed, endurance, a tall stature, general coordination, an ability to deal with load (42). Fast bowling strength and conditioning programs and guidelines are evident (37), however, the associations between physical qualities and fast bowling performance is not well researched. Pyne et al. (46) reported differences in physical predictors of peak bowling speed between junior and senior fast bowlers. Static jump, bench throw, countermovement jump (CMJ), and body mass explained 74% of the variance in peak bowling speed for junior fast bowlers (46). Fifty-four percent of the variance in peak bowling speed observed in senior fast bowlers was explained by the shoulder press throw, static jump, CMJ, arm length, and anterior-posterior chest depth (46). Wormgoor et al. (54) found that concentric shoulder extension strength at 60°·s⁻¹ was able to explain 15% of mean ball release speed in premier-standard fast bowlers. These physical qualities and others, such as reactive strength, lower-body strength, power-endurance, speed, repeat-sprint-ability, and flexibility have not been assessed and related to all measures of fast
bowling performance. A knowledge of these relationships would enhance the selection of exercises in a fast bowlers’ strength and conditioning program.

The relationships between fast bowling kinematics and bowling speed has been studied extensively. Worthington et al. (56) reported 73.6% of the variation in mean ball release speed could be explained by approach speed, knee flexion angle at ball release, upper trunk flexion from front-foot contact (FFC) to ball release (BR), and shoulder angle (bowling arm to trunk) at FFC in elite fast bowlers. Ferdinands et al. (14) found that 68.8% of the variation in ball speed to be explained by center of mass (COM) deceleration from back-foot contact (BFC) to FFC, COM velocity from FFC–BR, and height. High performance fast bowlers demonstrate significantly greater anterior-posterior ground reaction force and front-hip positive power compared to amateur fast bowlers \(p < 0.05\) (36). Glazier and Worthington (24) observed BR speed to significantly relate to COM velocity at BFC \(r = 0.499, p = 0.025\) and at FFC \(r = 0.508, p = 0.022\), in conjunction with the average COM horizontal acceleration from FFC–BR \(r = -0.544, p = 0.013\), and the change of horizontal velocity from FFC–BR \(r = 0.658, p = 0.002\). Portus et al. (45) reported a significant inverse relationship between shoulder segment counter-rotation in the transverse plane from BFC–FFC and bowling accuracy \(r = -0.542, p = 0.045\). The associations between other measures of fast bowling performance, such as variability of bowling speed and accuracy, have not been investigated with kinematic measures.

Physical qualities and their interactions with fast bowling kinematics is not well understood. High performance fast bowlers with greater trunk stability exhibited more front-knee flexion at front-foot impact during the fifth over \(r = -0.798, p = 0.001\) and eighth and final over \(r = -0.546, p = 0.043\) of the bowling spell (45). Loram et al. (34) identified a
positive relationship between peak torque of knee flexion at 60° s\(^{-1}\) and front-knee extension angle at FFC \(r = 0.58, p = 0.049\). The strength-endurance of the front-leg quadriceps muscles appears important, as when fatigued, knee flexion occurs in fast bowlers that exhibit a straight front-leg technique from FFC–BR, resulting in slower ball release speeds (10). This reinforces the need to explore the relationships between physical qualities, fast bowling kinematics, and fast bowling performance measures because these inter-relationships may yield important insights into how strength and conditioning may influence bowling performance. Therefore, the objective of this study was to investigate the relationships between selected physical qualities, kinematics, and measures of fast bowling performance.

**METHODS**

**Experimental Approach to the Problem**

Subjects completed six familiarisation sessions dispersed over three weeks, to learn the fast bowling assessment (16), and the technique and procedures of all physical capacity tests. Three testing sessions occurred on separate occasions, 4–7 days apart from each other, at the same time of day for the subjects. The first testing session comprised an eight-over (48 deliveries) fast bowling assessment (16), where fast bowling performance and selected bowling kinematics were assessed. The remaining two testing sessions involved physical capacity assessment, spread out to minimize fatigue between tests and sessions (Table 1). Prior to each testing session, subjects were instructed to refrain from alcohol and caffeine consumption for a 24-hour period, as well as any form of resistance training for a 48-hour period. Ambient temperature was controlled indoors and ranged from 19-21°C throughout testing sessions.
Subjects

Thirty-one male amateur club fast bowlers with a mean age, weight, and height of 21.7 ± 4.7 years, 82.0 ± 12.9-kg, and 1.82 ± 0.06-m respectively, recruited from the Ballarat Cricket Association (A and B grade level), served as the subjects. The mean structured resistance training and fast bowling experience of subjects was 1.4 ± 1.7 years and 9.1 ± 4.5 seasons, respectively. Fifteen subjects had no resistance training experience, while the others had a mean 2.7 ± 1.4 years of resistance training experience. It would have been ideal for all subjects to have at least one year of structured resistance training experience, however, this is typical of amateur fast bowlers. All procedures were approved by the University Human Research Ethics Committee and written informed consent was obtained for each subject or parent/guardian prior to the commencement of the study. Subjects were included if they were injury free at least six months prior to the time of testing.

Procedures

Fast Bowling Assessment. A standardized general and specific warm-up preceded assessment, and involved 20-m shuttle runs of progressive intensity, side to side shuffles, 15-m sub-maximal sprints, and dynamic stretches. Subjects delivered 10 warm-up balls of progressive intensity (60-95% perceived effort) to a variety of targets. A new 156-g two-piece red cricket ball (Tuf Pitch, Kookaburra, Melbourne, Australia) was used for the warm-up and subsequent assessment. Subjects were provided with this verbal instruction prior to assessment:

“Bowl as fast, accurate and consistently as possible as you would in a match.

We are measuring all of these elements. At different times throughout the test, you will be instructed to bowl some deliveries at maximal speed and some
deliveries with your preferred slower ball. Your speed and accuracy with these balls is also measured.”

The eight-over fast bowling test was conducted following published procedures (16). The test was performed indoors on a synthetic grass pitch, with an extended but enclosed portion of the run-up situated outside. Subjects delivered each ball to one of five targets at an instructed delivery speed (i.e., “maximal-effort”, “match-intensity”, and “slower-ball”, Table 2). These circular targets were situated on a suspended vinyl sheet that hung vertically and in line with the stumps at the batting end of the wicket. Subjects delivered to a batsman, who was instructed to evade the delivery only after it was released. The batsman adopted a middle stump “guard”, with each foot placed hip-width apart and either side of the popping crease. The batsman alternated right- and left-handed stance throughout the test to face an equal amount of deliveries either side (Table 2).

Ball release speed of each delivery was measured by a radar gun (Stalker Pro, Applied Concepts, Texas, USA). The radar gun was mounted on a tripod and positioned 1.37-m behind the popping crease, with a 0.3-m lateral shift from the line of middle stump, to avoid contact with each subject in the run-up. The radar gun was fixed at a height of 1.95-m, and an angle of 25° to capture point of release. Cosine effect error in ball release speed was corrected for in a purpose-made spreadsheet by multiplying measured speed by 0.906 (i.e., cosine of 25°).
The accuracy of each delivery was captured by a high-speed camera (PCI 2000 S, Redlake Imaging Corporation, CA, USA) that operated at 250 frames per second and with a shutter speed of 0.004-s. The high-speed camera was mounted on a tripod and positioned 0.36-m from the popping crease, with a 0.3-m lateral shift from the line of middle stump, to avoid contact with each subject in the run-up. The high-speed camera was fixed at a height of 1.47-m, and an angle of 10° to accommodate the entire target sheet. Recorded video footage was imported into Dartfish Connect (Version 7.0, Dartfish, Melbourne, Australia). The measurement function was calibrated in Dartfish Connect by drawing a vertical line from the center of the bouncer target to the top of middle stump target, which was exactly 1.0-m apart. The radial error, along with $x$ and $y$ coordinates were calculated for each delivery (43).

The intensity of each delivery was recorded by asking subjects after each delivery: “how hard was that delivery out of 100%?” This measure was termed the delivery rating of perceived effort (RPE), and is capable of discriminating between maximal-effort and match-intensity deliveries in fast bowlers (16). It was chosen in favour of the Borg CR-10 RPE scale (6), because in pilot testing, subjects understood and related better with the percentage method when bowling. The intraclass correlation coefficient (ICC), coefficient of variation (CV), and standard error of measurement (SEM) of all fast bowling performance measures were established in prior reliability testing in a smaller sample of amateur fast bowlers (Table 3).

Bowling Kinematic Assessment. Prior to the fast bowling assessment, subjects were marked with retro-reflective tape (3-cm square) on the lateral surface of the bowling front-leg while
standing. The tape was placed in four locations; 5- and 20-cm below the greater trochanter in line with the lateral border of the knee-joint center, and 5- and 20-cm above the lateral malleolus in line with the lateral border of the knee-joint center (52).

A digital high-definition video camera (Sony HXR-MC50P, Sony Corporation, Tokyo, Japan) operating at 25 frames per second, with a pre-set shutter speed of two milliseconds, captured two-dimensional bowling-kinematic footage in the sagittal plane for each delivery. The high-definition video camera was mounted on a tripod 1.75-m above the ground, and was positioned 6.60-m away from and parallel with the popping crease at the bowling end, and on the contralateral side of the subjects’ bowling-arm. A 500-W floodlight was positioned next to the camera, and shone onto a white vinyl backdrop positioned on the ipsilateral side of the subjects’ bowling arm, to facilitate easier detection of ball release. The footage of each delivery was later imported into Dartfish Connect (Version 7.0, Melbourne, Australia).

In Dartfish Connect, the following two-dimensional bowling-kinematic variables were calculated for each delivery: 1) delivery step length; the BFC–FFC distance, 2) BFC–FFC duration, 3) FFC–BR duration, 4) front-knee angle at FFC, and 5) front-knee angle at BR (Figure 1). To facilitate the calculation of delivery step length, a known distance between the two crease markings at the bowling end of the wicket were used, and set to 1.22-m. In addition, approach speed was measured by a dual-beam electronic timing system (Swift Performance Equipment, Lismore, Australia), with a 10-ms timing resolution. Timing gates were positioned in line with and 5-m behind the popping crease at the bowling end of the wicket. These variables were selected because of significant relationships to ball release speed in elite / professional fast bowlers (14,24,34,56). It is acknowledged that a three-dimensional system is more appropriate for such analysis (4), but the two-dimensional system
was all that was available at the time of data collection. The front-leg knee angle at FFC and
BR could not be calculated for every subject, due to external or internal tibial rotation on the
due to external or internal tibial rotation on the femur causing parallax error. Nevertheless, the ICC, CV, and SEM were established in prior
reliability testing in a smaller sample of amateur fast bowlers (Table 3). Approach speed was
determined to be the only kinematic variable with unacceptable reliability, with a coefficient of
variation greater than 10% (50) and ICC less than 0.8 (53). The SEM was not calculated for
this variable because it violated the normal distribution (2).

20 Countermovement Jump Test. This test was included as a measure of lower-body power
and power-endurance. This physical capacity might be important as a fast bowler’s run-up
involves several powerful steps to accelerate to near-maximal speed prior to jumping onto the
pitch and delivering the cricket ball. A portable force platform (400 Series Force Plate,
Fitness Technology, Adelaide, Australia) and linear position transducer (PT5A, Fitness
Technology, Adelaide, Australia) were calibrated prior to the test. The sampling rate for the
force plate and linear position transducer was set to 600-Hz. Displacement was “zeroed” with
subjects standing tall and still on the force platform. The force platform was also zeroed with
the subject standing off to the side. The subject resumed a standing position on the force
platform, and was instructed to “jump for maximal height each repetition”, and to wait for a
“go” command prior to each jump. In attempt to maintain a horizontal dowel during the test,
subjects were asked to maintain downward pressure of the dowel on the upper trapezius. The
linear position transducer was attached to the end of the dowel.
The test involved 20 CMJs; one CMJ was performed every three seconds. The test comprised a self-selected dip followed by an explosive jump and a landing of self-selected depth to absorb force. Subjects were required to “reset” into a fully erect trunk position prior to the next CMJ. Encouragement was provided each repetition. Maximal height and concentric peak power were calculated for each repetition in the Ballistic Measurement System Software (Version 2011.2.0, Innervations, Australia). From this data, the largest value obtained for maximal height and concentric peak power in the first three CMJs were used to represent lower-body power. For lower-body power-endurance, the mean maximal height and concentric peak power from the 20 CMJs were calculated in a purpose-made Microsoft Excel spreadsheet (Redmond, WA). Although the test-retest reliability of peak power in a CMJ test involving 20 repetitions has not been established, the peak power from a jump squat test comprising 30 repetitions demonstrates excellent test-retest reliability (ICC = 0.96, CV = 3.2%) (1).

**20 Bench Press Throw Test.** This test was included as a measure of upper-body power and power-endurance. Fast bowlers demonstrate powerful contractions of the upper-body during the FFC–BR phase (13). The pectoralis major is strongly activated during the propulsive phase of baseball pitching (25); a motion similar to fast bowling. The BPTs were performed in a Smith Machine, to allow easier measurement of vertical displacement (1). Subjects adopted a supine position on a bench, and were positioned in the center of a Smith Machine, with the bar vertically aligned with the subjects’ nipple. Subjects had to maintain contact with the bench (head and back) and with the floor (left and right feet). A pronated and slightly-wider than shoulder width grip was adopted. A linear position transducer (PT5A, Fitness Technology, Adelaide, Australia) was attached to the end of a 20-kg bar, to permit the measurement of throw height. No extra weight was added. The linear position transducer was
calibrated to enable reliable collection of throw height. Displacement was “zeroed” when
each subject un-racked the bar and fully extended their arms. Subjects were instructed to
“throw for maximal height each repetition”, and to wait for a “go” command prior to each
throw.

The test involved 20 BPTs; one BPT was performed every three seconds. The test
comprised a self-paced dip followed by an explosive throw and a “catch” to absorb the force.
Subjects were required to “reset” to a fully extended arm position prior to the next BPT.
Encouragement was provided each repetition. Maximal height was calculated each repetition
From this data, the largest value obtained for maximal height in the first three BPTs was
chosen to represent upper-body power. For upper-body power-endurance, the mean maximal
height from the 20 BPTs was calculated in a purpose-made Microsoft Excel spreadsheet
(Redmond, WA). Although the test-retest reliability of peak and mean height values in a BPT
test involving 20 repetitions is not known, the peak power from a BPT test comprising 30
repetitions exhibits excellent reliability (ICC= 0.92, CV = 6.3%) (1).

Half Squat Test. This test was included as a measure of leg pushing strength. This physical
capacity may be important for fast bowlers, as they typically experience large vertical and
horizontal ground reaction forces during the FFC–BR phase (4). Furthermore, lower-body
strength may assist the transfer of kinetic energy to the cricket ball. Due to the minimal
resistance training experience within many of the subjects, a three-repetition maximum (RM)
test was chosen in preference to a 1RM. The test was conducted in a Smith Machine to
improve subject safety.
In this test, subjects stood in the center of the Smith Machine, and placed the bar onto the upper trapezius muscle. They adopted a hip-width stance, and squatted to 90° knee flexion; assessed with a goniometer. Masking tape was placed on the cage in line with the bar at this depth. This marker was used for the checking of depth, and to provide feedback to the subject where necessary. Subjects were instructed to “lower and raise the bar with control each repetition”, and listen for the assistant to say “up” before raising the bar.

A warm-up set of five repetitions were initially performed with a 20-kg bar to ensure correct technique. From each set following, four repetitions were conducted with a safe but gradual increase in load (based on observation and subject feedback), until “technical failure” occurred on the fourth repetition. Technical failure was evident if subjects could not maintain correct squatting technique (e.g., neutral spine), or could not squat to an erect position (3). A four minute passive rest was adopted between test sets to allow sufficient time for central nervous system recovery (5). Encouragement was provided each test set. The 3RM load was usually determined within five test sets, which minimized the effects of fatigue on test performance (48). While the test-retest reliability of the 3RM half squat in a Smith Machine is not established, the 3RM Smith Machine parallel squat exhibits excellent test-retest reliability (ICC = 0.92) (48).

Bench Press Test. This test was included as a measure of upper-body pushing strength. Chelly et al. (8) reported bench press strength to significantly correlate with throwing velocity in handball ($r = 0.56, p < 0.05$). Due to the minimal resistance training experience within many of the subjects, a three-repetition maximum (RM) test was chosen in preference to a 1RM. The test was conducted in a Smith Machine to improve subject safety. In this test, subjects adopted a supine position with head and back in contact with the bench, and left and
right foot in contact with the ground (3). A pronated but slightly-wider than shoulder-width grip was used, and the bar was lowered to gently touch the mid-chest region (nipple line). Subjects were instructed to “lower and raise the bar with control each repetition”.

A warm-up set of five repetitions with a 20-kg bar was initially performed to ensure correct bench press technique. From each set following, four repetitions were conducted with a safe but gradual increase in load (based on observation and subject feedback), until “technical failure” occurred on the fourth repetition. Technical failure was evident if subjects could not maintain correct bench press technique (i.e., head, feet, or back raised off bench), or could not raise the bar to a fully-extended arm position (3). A four minute passive rest was adopted between test sets to allow sufficient time for central nervous system recovery (5). Encouragement was provided each test set. The 3RM load was usually determined within five test sets, which minimized the effects of fatigue on test performance (48). This test exhibits excellent test-retest reliability (ICC = 0.97) (48).

Pull-up Test. This test was included as a measure of upper-body pulling strength, and assesses the latissimus dorsi muscle (57), which is strongly activated during the propulsive phase of baseball pitching (25). The 1RM test was chosen in preference to the 3RM used for the half-squat and bench press tests, as some subjects could not perform multiple repetitions with their body-mass during familiarisation period. This test was performed in a Smith Machine, where the bar could be adjusted and fixed to a height that subjects could just reach when standing. Subjects adopted a pronated but slightly wider than shoulder-width grip on the Smith Machine bar. Without jumping, subjects were required to pull their body upwards so that their chin cleared the bar. Upon lowering, they had to fully extend their arms.
A warm-up set of three repetitions was initially performed at the subjects’ bodyweight. Some subjects could only achieve one repetition at their bodyweight, while others failed to complete one repetition. Subjects who could not complete the test did not receive a score. Nevertheless, for those with sufficient strength, two repetitions were conducted from each set afterwards, with a safe but gradual increase in load until “technical failure” occurred on the second repetition. Technical failure was evident in this test if subjects could not complete full range of motion (i.e., raise their chin above the bar) (29). Load was increased via a weight-belt and chain that accommodated weight plates. A four minute passive rest was adopted between test sets to allow sufficient time for central nervous system recovery (5).

Encouragement was provided each test set. The 1RM load was usually determined within five test sets, which minimized the effects of fatigue on test performance (48). Performance on this test was characterized by the absolute mass lifted (body-mass plus additional weight). Although the test-retest reliability of the 1RM pull-up is not established, the maximal amount of pull-ups at 80% 1RM exhibits excellent test-retest reliability (ICC = 0.92–0.96) (29).

**Plank Test.** This test was included as a measure of isometric strength-endurance in the trunk, in particular, the transversus abdominis muscle (28). The transversus abdominis muscle isometrically stabilises the trunk during dynamic movements (9), such as fast bowling. Each subject was required to support their weight with their forearms and toes. Both elbows were aligned under each shoulder, and palms faced down in contact with the exercise mat. Each subject was instructed to “lift their pelvis off the mat, maintain a neutral spine, and hold for as long as possible”. Encouragement was continually provided throughout the test. A digital high-definition video camera (Sony HXR-MC50P, Sony Corporation, Tokyo, Japan) collected footage, which was later imported into Dartfish Connect for the analysis of the total continuous time each subject held correct technique. The test was terminated on analysis
when the subject was unable to maintain neutral spine. Reece (47) reported acceptable reliability for this test \( (r = 0.86) \).

**Side Plank Test.** This test was included as a measure of isometric strength-endurance, in particular, the external oblique muscle on the supporting-limb side. The external-obliques are active during the fast bowling motion, where they assist in ipsilateral trunk rotation, flexion, and lateral trunk flexion (30). Each subject was required to support their weight on a forearm and foot. The supporting-arm elbow was aligned under the shoulder, with the palm of the hand facing down on an exercise mat. The non-supporting hand was placed on the pelvis. The non-supporting foot was positioned on top of the supporting foot. Subjects were instructed to “lift their pelvis off the mat and maintain a straight line, while holding for as long as possible”. Encouragement was continually provided throughout the test. A digital high-definition video camera (Sony HXR-MC50P, Sony Corporation, Tokyo, Japan) collected footage, which was later imported into Dartfish Connect for the analysis of the total continuous time each subject held correct technique. The test was terminated on analysis when the subject was unable to maintain neutral spine. Subjects completed this test on both sides of the body, with a two-minute rest between tests. The maximal duration completed on each side of the body was retained for analysis, and split into bowling-arm side and non-bowling-arm side. McGill et al. (35) reported excellent reliability in this test \( (r = 0.99) \).

**Repeat-Sprint Test.** This test was included to measure acceleration speed and repeat-sprint ability. The approach speed of elite fast bowlers can reach 76-78% of the peak running speed determined in a 30-m sprint test (11). Fast bowlers repeatedly perform these efforts within an over, across all match formats (41). Three pairs of dual-beam electronic timing gates (Swift Performance Equipment, Lismore, Australia), were positioned at 0-, 10-, and 20-m. The
timing gates had a timing resolution of 0.01-s. Synthetic turf of 12-mm pile height (Tuff Turf, Bunnings, Australia) was placed on top of an all-purpose floor to minimize slipping and affixed by cloth tape. A white starting line was marked on the synthetic turf at 0-m.

Subjects completed five 20-m runs at 50%, 60%, 70%, 80%, and 90% of maximum effort, to ensure readiness for the test. Subjects adopted a stationary split stance technique, with the preferred leg positioned at the start line, and opposite arm forward. Following the warm-up, subjects were instructed to “sprint as fast as possible for each repetition”, with no “rocking” backwards and forwards at the starting line. Subjects completed 10 x 20-m sprints, with one sprint occurring every 20-s. The length of sprint was chosen as it is similar to an elite fast bowlers’ run-up (11). Ten sprints were chosen as a means of overload; as fast bowlers are usually conditioned to at least six efforts per over in a match. After each sprint, subjects jogged back to the starting line, and were provided a five second countdown for the next sprint. Encouragement was continuously provided throughout the test. The first 20-m sprint of this test was taken as a measure of acceleration speed, while the accumulative time from the 10 sprints was used as a measure of repeat-sprint ability. Although the test-retest reliability of the 10 x 20-m repeat-sprint test is not understood, Spencer et al. (49) reported the accumulative time from 6 x 30-m repeat-sprints to demonstrate excellent reliability (CV = 0.7%). Furthermore, Gabbett et al. (20) observed excellent reliability for 10-m sprint time (ICC = 0.87, CV = 1.9%) and 20-m sprint time (ICC = 0.96, CV = 1.3%).

 Drop Jump Test. This test was included as a measure of lower-body reactive strength (59); the ability to change quickly from an eccentric to concentric muscular contraction (18). This physical capacity may be important for fast bowlers who adopt a “flexor-extender” front leg technique (44) during the FFC–BR phase. The flexor-extender front leg technique is
associated with larger ground reaction forces, and faster times to reach peak force (44); this
technique may be important for fast bowlers to produce greater ball release speeds.

The drop jump technique involved subjects standing on the box, with the toes hanging
over the edge. Hands were placed on hips, and remained in position throughout the test.
Subjects were instructed to “jump for maximal height and minimal ground-contact time”
(59). Subjects stepped off the box, landed on their forefeet with extended legs, and performed
an explosive jump. They were instructed to land with fully extended legs from the rebound
jump, but to flex at the hips, knees, and ankles to absorb the vertical ground reaction forces
(59). A contact mat system (Swift Performance Equipment, Queensland, Australia) and
custom-made computer software was used to compute jump height from ground contact time
data (58). Jump height was calculated using previously established methods (17). The
reactive strength index score of each jump was calculated (12). The initial box height was set
to 30-cm, and was progressively increased every three repetitions by 15-cm, until the reactive
strength index score diminished with an increase in box height. The maximal possible box
height was set to 75-cm. The highest reactive strength index score obtained, irrespective of
box height, was used for analysis. Flanagan and Comyns (17) reported the reactive strength
index score to exhibit excellent reliability (ICC = 0.967).

Maximal Multi-Stage 20-m Shuttle Run Test. This test was selected as a measure of aerobic
power (40); a physical capacity thought to enhance recovery between repeated sprints (22).
The test was conducted following established protocols (32). Subjects were encouraged
throughout the entire test. The relative maximal oxygen consumption and utilisation score
($\dot{V}O_{2\text{max}}$) was estimated by the total of 20-m shuttles completed (40), and served as the
measure of aerobic power for each subject in this investigation. Leger et al. (31) reported excellent test-retest reliability for the maximal multi-stage 20-m shuttle run test ($r = 0.95$).

**Active Straight-Leg Raise Test.** This test was included as a measure of hamstring flexibility (21); a quality that may relate to the favourable extended front-leg technique for the development of bowling speed. The iliocristale, greater trochanter, and lateral knee joint center were marked on the subjects’ bowling front leg. Subjects adopted a supine position on a massage table with legs fully extended and feet hip-width apart. Each subject was instructed to “bring their front leg towards their face as far as possible while keeping the leg straight and maintaining a neutral foot angle”. The subjects’ uninvolved leg rested in an extended position, and in full contact with the table along with the head and spine. The uninvolved leg was held down by the examiner, and was not allowed to be contracted by the subject during the test. Subjects completed this test when warm, as they had performed lower-body physical tests beforehand (Table 1). A digital high-definition video camera (Sony HXR-MC50P, Sony Corporation, Tokyo, Japan) collected footage in the sagittal plane, which was later imported into Dartfish Connect to determine the largest range of motion (with correct technique), and to estimate the angle of the pelvis in relation to the iliocristale, based on the location of markers. The reflex angle was calculated by subtracting the acute or obtuse angle from 180° (starting position). Although the test-retest reliability of the active straight-leg raise test is unclear, Herrington et al. (26) observed the passive straight-leg raise test to present excellent reliability (ICC= 0.93, SEM = 2.5°).

**Shoulder Horizontal Abduction Test.** This test was included as a measure of pectoralis major flexibility (30). The ability to delay circumduction of the bowling-arm correlates with bowling speed (56). Such a delay, combined with vigorous trunk flexion, is suggested to
create an “inertial lag” on the bowling-arm, where a pre-stretch occurs in the anterior shoulder musculature (i.e., pectoralis major) (15). This pre-stretch is thought to store elastic energy, which may assist with faster bowling-arm circumduction and perhaps greater bowling speed (15). The acromiale of each scapula was marked in conjunction with the lateral elbow joint center for the bowling-arm side only. Subjects adopted a supine position on a massage table, and laterally positioned their body to the edge of the table, ipsilateral to the bowling-arm. The examiner placed gentle pressure on the contralateral shoulder to prevent the subject from rolling off the table. Subjects were passively placed in 90° shoulder abduction with a supinated forearm. From this position, the subject was instructed to “let their arm hang as low as possible, with their palm facing the ceiling, while remaining relaxed”. An assistant stood in the sagittal plane and ensured the bowling-arm maintained 90° shoulder abduction during the test. A digital high-definition video camera (Sony HXR-MC50P, Sony Corporation, Tokyo, Japan) collected footage in the frontal plane, which was imported into Dartfish Connect to determine the largest range of motion, and to estimate the reflex angle of the shoulder segment (acromiale to acromiale) in relation to the lateral elbow joint center (Figure 2). This test is novel and specific to fast bowling, but its reliability is not established.

**Anthropometric Tests.** Body mass was obtained with the subject standing on a set of digital scales, with minimal clothing (i.e., no shoes, socks, jumpers, pants), and was recorded to the nearest 0.01 kg. Standing height was assessed on a stadiometer, with no shoes or socks, following the free-standing method (51). Reach height of the bowling-arm was measured (Figure 3), with the subject standing fully erect against a wall, and raising their bowling arm overhead as high as possible while maintaining level shoulders (i.e., no scapular elevation or
upward rotation). This quality was assessed as Glazier et al. (23) postulated that a longer bowling-arm will increase bowling speed; given there is no change in bowling-arm angular velocity. The examiner placed downward pressure on the subjects’ shoulders to maintain a level position. An assistant marked the highest point of reach with chalk. A ruler was used to measure reach height. The reach height is a novel test specifically designed for fast bowling, but its reliability is not established.

Statistical Analyses

From the bowling speed data, three values were calculated: 1) peak ball release speed; the mean of all four maximal-effort deliveries, 2) mean ball release speed; comprising all 48 deliveries, and 3) variability of ball release speed, the standard deviation of all 48 deliveries. From the bowling accuracy data, two values were calculated: 1) mean radial error (43), and 2) bivariate variable error (43); from all 48 match-intensity deliveries.

The normality of each variable was assessed using a Shapiro-Wilk test in IBM SPSS Statistics (Version 24.0, IMB Corp., Armonk, NY). As many variables violated the normal distribution, Spearman’s rank order correlations (two-tailed) were performed instead of multiple regression analyses to assess the relationships between selected physical qualities, bowling kinematics, and bowling performance measures. For all correlations, missing data were treated by excluding cases pairwise, not listwise. The strength of correlations were classified using modified Hopkins (27) thresholds / descriptors as follows: trivial ($r < 0.10$), small ($r = 0.10–0.29$), moderate ($r = 0.30–0.49$), large ($r = 0.50–0.69$), very large ($r = 0.70–0.90$), and nearly perfect ($r > 0.90$). Significance was set at $p < 0.05$ for all analyses.
RESULTS

*Relationships between selected physical qualities and fast bowling performance measures.*

Large positive relationships were observed between 1RM pull-up strength and peak and mean ball release speeds (both $r_s = 0.56$, $p = 0.005$, Table 4). Twenty-metre sprint time exhibited moderate negative relationships between peak and mean ball release speeds ($r_s = -0.42$, $p = 0.022$; $r_s = -0.37$, $p = 0.044$, respectively, Table 4). Both 10-m and 20-m sprint time were moderately and positively related to mean radial error ($r_s = 0.41$, $p = 0.030$; $r_s = 0.38$, $p = 0.037$, respectively, Table 4). The peak height and largest concentric peak power achieved in three CMJs, in conjunction with the mean concentric peak power from 20 CMJs revealed moderate negative correlations to mean radial error ($r_s = -0.39$, $p = 0.036$; $r_s = -0.41$, $p = 0.031$; $r_s = -0.45$, $p = 0.020$, respectively, Table 4). No other statistically significant relationships were observed between physical capacities and bowling performance measures.

*Relationships between selected physical qualities and fast bowling kinematics.* Three-repetition maximum bench press strength was moderately and positively related to approach speed ($r_s = 0.41$, $p = 0.037$, Table 5). A greater performance on the active straight-leg raise test was moderately and positively associated with the BFC–FFC duration ($r_s = 0.46$, $p = 0.013$, Table 5). Subjects with greater bowling-arm reach height were typically slower throughout the FFC–BR phase ($r_s = 0.52$, $p = 0.004$, Table 5), whereas those with a higher predicted $\dot{V}O_2_{max}$ were faster throughout the FFC–BR phase ($r_s = -0.42$, $p = 0.029$, Table 5). Mean BPT height from 20 repetitions displayed a large negative correlation to front-leg knee
angle at FFC ($r_s = -0.57, p = 0.011$, Table 5). No other statistically significant relationships were observed between physical capacities and bowling kinematic measures.

**INSERT TABLE 5 ABOUT HERE**

*Relationships between selected fast bowling kinematics and fast bowling performance measures.* A longer delivery step length was typically associated with faster peak and mean ball release speeds ($r_s = 0.49, p = 0.005$; $r_s = 0.51, p = 0.003$, respectively, Table 6). A shorter FFC–BR phase was related to peak and mean ball release speeds ($r_s = -0.44, p = 0.013$; $r_s = -0.45, p = 0.011$, respectively, Table 6). Subjects with a faster approach speed typically exhibited less bivariate variable error; that is, they were more consistently accurate ($r_s = -0.36, p = 0.050$, Table 6). A greater front-leg knee angle (i.e., more knee extension) at ball release was moderately and positively related to bivariate variable error ($r_s = 0.41, p = 0.036$, Table 6). No other statistically significant relationships were observed between bowling kinematic variables and bowling performance measures.

**INSERT TABLE 6 ABOUT HERE**

**DISCUSSION**

The large positive correlations between 1RM pull-up strength and peak and mean ball release speeds may highlight the importance of the latissimus dorsi muscle during cricket fast bowling. This muscle is strongly activated during the propulsive phase of baseball pitching (25); a motion exhibiting a general proximal-to-distal segmental sequencing pattern (39), similar to fast bowling (15). The latissimus dorsi extends and internally rotates the glenohumeral joint (30), and would thus contribute to the torque produced by bowling-arm
glenohumeral joint during circumduction. Strengthening this muscle might therefore be important, especially as Glazier et al. (23) observed bowling-arm angular velocity to not significantly relate to ball release speed ($r = 0.36, p > 0.05$) (23). This contention is further supported by Wormgoor et al. (54), who reported ball release speed to positively associate with internal rotation strength ($r = 0.43, p = 0.02$) and extension strength ($r = 0.39, p = 0.04$) of the glenohumeral joint.

The moderate negative correlations observed between 20-m sprint time and ball release speed possibly indicate the importance of acceleration speed for cricket fast bowling. The association between these two variables cannot be explained by any of the kinematic variables collected in this investigation. Twenty-metre sprint time exhibited a small and non-significant relationship with approach speed ($r_s = -0.15, p = 0.427$); a quality significantly correlated with ball release speed (11,14,23). Furthermore, 20-m sprint time demonstrated a small and non-significant association with the FFC–BR phase ($r_s = 0.26, p = 0.167$); a kinematic variable associated with peak ball release speed ($r_s = -0.44, p = 0.013$) and mean ball release speed ($r_s = -0.45, p = 0.011$) in this study. Further research is warranted to better understand the relationship of acceleration speed to peak and mean ball release speeds.

As previously mentioned, a shorter FFC–BR phase demonstrated a moderate negative and significant associations with peak and mean ball release speeds. This is in contrast with Glazier and Worthington (24), who reported a moderate but non-significant association between FFC–BR duration and mean ball release speed ($r = -0.31, p = 0.19$). Nevertheless, the subjects in their study exhibited shorter FFC–BR phases (80–120-ms), and bowled faster (34.9-m·s$^{-1}$) compared to subjects in the current investigation (105–150-ms, 28.8-m·s$^{-1}$) respectively). Only two of the physical capacities measured in this study displayed a
significant relationship to the FFC–BR phase; reach height and predicted VO$_2$max. A greater
reach height typically resulted in a slower FFC–BR phase; possibly by increasing the torque
and reducing the angular velocity about the glenohumeral joint. Note, this variable was not
significantly related to peak or mean ball release speeds. Theoretically, a longer bowling arm
increases the acceleration path of the ball, which should increase bowling speed providing
angular velocity is unchanged (23). Predicted VO$_2$max exhibited a moderate negative and
significant relationship to the FFC–BR phase. This relationship may be explained by the
aerobic energy system’s ability in prolonging the onset of fatigue. As fast bowlers fatigue, all
of the working muscles would be expected to contract slower, and thereby extend the
duration on the FFC–BR phase. Furthermore, a well-developed aerobic capacity should assist
with the repeat-sprint ability demands of fast bowlers, and consequently allow a fast bowler
to maintain their approach speed each delivery. Predicted VO$_2$max exhibited small and trivial
non-significant relationships with peak and mean ball release speeds respectively.

Delivery step length demonstrated a moderate and large positive and significant
relationships with peak and mean ball release speeds ($r_s = 0.49, p = 0.005; r_s = 0.51, p =
0.003$, respectively) in this investigation. This finding is in agreement with Worthington et al.
(55), who observed a large relationships between front-leg plant angle (a variable similar to
step length) and ball release speed ($r = 0.52, p = 0.02$). A longer delivery step may facilitate
greater trunk flexion over the subjects’ center of gravity, which would create an inertial lag
on the anterior chest musculature of the bowling arm; a mechanism for enhancing bowling
speed (15). There were no physical capacities that significantly related to delivery step
length, indicating that this variable may be influenced by other kinematic variables, such as
approach speed (14).
Acceleration speed (10-m and 20-m sprint time), lower-body power (peak concentric power and height in three CMJs), and lower-body power-endurance (mean peak concentric power in 20 CMJs) qualities were significantly related (small–moderate strength) to better bowling accuracy performance (i.e., reduced radial error). As fast bowling is an explosive intermittent activity, adequate acceleration speed, in conjunction with lower-body power and power-endurance may prolong time to fatigue during a bowling spell, and preserve the ability for the fast bowler to control the line and length of the delivery. Further analysis revealed that the subjects adopted slightly faster approach speeds as delivery effort increased; “maximal-effort” delivery: 5.6-m·s⁻¹, “match-intensity” delivery: 5.5-m·s⁻¹, and “slower-ball” delivery: 5.4-m·s⁻¹. It is likely that lower-body power and power-endurance would accommodate such a marginal increase in approach speed, and thus maintain the same level of bowling accuracy with greater delivery effort.

Approach speed reached borderline significance with bivariate variable error (i.e., variability of bowling accuracy) ($r_s = -0.36$, $p = 0.050$). While it’s difficult to understand this relationship, it may be partially explained by the front-leg knee angle at the moment of ball release. Further analysis revealed that approach speed and front-leg knee angle at ball release were moderately and negatively linked to each other ($r_s = -0.42$, $p = 0.029$); with the latter also moderately and positively related to bivariate variable error ($r_s = 0.41$, $p = 0.036$). These results suggest that subjects with a faster approach speed extended the front-leg to a greater extent at the moment of ball release, which in turn related to less variability in bowling accuracy performance. This is a novel finding, and one that confirms the importance of the extended front-leg technique at ball release; which is typically known to positively and significantly relate with ball release speed (34,54,56). Further research is warranted to better
understand the mechanism behind the reduced variability in bowling accuracy performance with these kinematic qualities.

While this investigation was able to reveal some novel and interesting insights into the relationships between selected physical qualities, bowling kinematics, and bowling performance measures, there were many weak and statistically insignificant correlations. This may be partially explained by the amateur cohort of fast bowlers in this study. Although speculative, the subjects in this study would be expected to possess greater technical flaws compared to elite / professional counterparts. This could affect how physical qualities transfer to fast bowling performance. For example, Frane et al. (19) found that the correlation of biomotor abilities (i.e., strength, power, speed) and javelin throwing performance was dependent on mastery of throwing technique. Weaker and non-significant correlations were observed between biomotor abilities and throwing performance in those with poorer throwing techniques. That particular study highlights the importance of improving segmental sequencing coordination (15) so that the biomotor abilities can better transfer to performance. Therefore, the results of this study cannot be applied to elite fast bowlers, as the relationships between physical qualities, bowling kinematics, and bowling performance measures may change with bowlers with fewer technical deficiencies.

PRACTICAL APPLICATIONS

Strength and conditioning coaches may be able to enhance fast bowling performance in amateur competitors by developing some of the significant physical qualities identified in this investigation. For example, peak and mean ball release speeds may be improved with pull-up strength training and acceleration speed training (10–20-m). Bowling accuracy may be improved with acceleration speed training, along with exercises that develop lower-body
power and power-endurance training. Skills coaches may be able to develop fast bowling performance in amateur competitors by addressing the significant bowling kinematic variables observed in this investigation. For example, coaching methods that are designed to lengthen the delivery step and improve the speed throughout the FFC–BR phase may be enhance peak and mean ball release speeds. Whereas developing approach speed may result in a more extended front-leg at ball release, which may enhance the consistency of bowling accuracy in fast bowlers. Although these training recommendations are made based on the statistically significant correlations identified in this study, training interventions are required to validate these relationships.
REFERENCES


55. Worthington, P, King, M, and Ranson, C. Does ‘optimal’ performance necessitate higher ground reaction forces? A fast bowling perspective. In: International


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Figure Legends

Figure 1. A) Marker placement at back foot contact and calibration of delivery step length. B) Marker placement at front foot contact and calculation of delivery step length and front-leg knee angle. C) Calculation of front-leg knee angle at moment of ball release. Back foot contact to front foot contact duration = 0.8-s, and front foot contact to ball release duration = 0.48-s in this example.

Figure 2. Measurement of shoulder horizontal abduction angle, in the subjects’ bowling arm only.

Figure 3. Measurement of reach height in the bowling-arm only.
Figures

Figure 1.

Note: Image format = *png. Print in black and white. Permission obtained from subjects in this figure.
Figure 2.

Note: Image format = *png. Print in black and white. Permission obtained from subject in this figure.
Figure 3.

Note: Image format = *png. Print in black and white. Permission obtained from subjects in this figure.
## Tables

### Table 1. Physical test battery employed over two testing sessions.

<table>
<thead>
<tr>
<th>Test #</th>
<th>Testing Session 2</th>
<th>Testing Session 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20 Countermovement Jump</td>
<td>Drop Jump</td>
</tr>
<tr>
<td>2</td>
<td>Standing Height</td>
<td>Half Squat</td>
</tr>
<tr>
<td>3</td>
<td>Reach Height</td>
<td>Bench Press</td>
</tr>
<tr>
<td>4</td>
<td>Body Mass</td>
<td>Pull-Up</td>
</tr>
<tr>
<td>5</td>
<td>20 Bench Press Throw</td>
<td>Plank</td>
</tr>
<tr>
<td>6</td>
<td>Repeat Sprint</td>
<td>Side Plank on Bowling Arm</td>
</tr>
<tr>
<td>7</td>
<td>-</td>
<td>Side Plank on Non Bowling Arm</td>
</tr>
<tr>
<td>8</td>
<td>-</td>
<td>Active Straight Leg Raise</td>
</tr>
<tr>
<td>9</td>
<td>-</td>
<td>Shoulder Horizontal Abduction</td>
</tr>
<tr>
<td>10</td>
<td>-</td>
<td>Multistage 20-m Shuttle Run</td>
</tr>
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</table>
Table 2. Delivery sequence in the fast bowling assessment.

<table>
<thead>
<tr>
<th></th>
<th>Overs 1 and 5</th>
<th>Overs 2 and 6</th>
<th>Overs 3 and 7</th>
<th>Overs 4 and 8</th>
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<tr>
<td>Ball 1</td>
<td>OFF / RH / MI</td>
<td>OFF / LH / MI</td>
<td>OFF / LH / MI</td>
<td>OFF / RH / MI</td>
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<tr>
<td>Ball 2</td>
<td>OFF / RH / MI</td>
<td>OFF / LH / MI</td>
<td>OFF / LH / MI</td>
<td>OFF / RH / MI</td>
</tr>
<tr>
<td>Ball 3</td>
<td>OFF / RH / MI</td>
<td>OFF / RH / MI</td>
<td>OFF / LH / MI</td>
<td>OFF / LH / MI</td>
</tr>
<tr>
<td>Ball 4</td>
<td>OFF / RH / MI</td>
<td>OFF / RH / MI</td>
<td>OFF / LH / MI</td>
<td>OFF / LH / MI</td>
</tr>
<tr>
<td>Ball 5</td>
<td>OFF / RH / ME</td>
<td>BOU / RH / MI</td>
<td>OFF / LH / ME</td>
<td>BOU / LH / MI</td>
</tr>
<tr>
<td>Ball 6</td>
<td>MID / RH / SB</td>
<td>YOR / RH / MI</td>
<td>MID / LH / SB</td>
<td>YOR / LH / MI</td>
</tr>
</tbody>
</table>

RH = right-handed batsman; LH = left-handed batsman; OFF = outside off stump target; MID = top of middle stump target; BOU = target near batsman’s head; YOR = target near base of middle stump; MI = match-intensity delivery; ME = maximal-effort delivery; SB = slower-ball delivery.
Table 3. Test-retest reliability data for fast bowling performance measures and selected fast bowling kinematic variables.

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>Trial 1</th>
<th>Trial 2</th>
<th>ICC</th>
<th>SEM</th>
<th>CV (%)</th>
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</thead>
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<tr>
<td></td>
<td></td>
<td>Mean ± SD</td>
<td>Mean ± SD</td>
<td></td>
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<td><strong>Fast Bowling Performance Variables</strong></td>
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<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Peak Ball Release Speed (m·s⁻¹)</td>
<td>13</td>
<td>26.4 ± 1.9</td>
<td>26.4 ± 2.0</td>
<td>0.975</td>
<td>0.3</td>
<td>1.3</td>
</tr>
<tr>
<td>Mean Ball Release Speed (m·s⁻¹)</td>
<td>13</td>
<td>25.6 ± 2.0</td>
<td>25.6 ± 2.0</td>
<td>0.987</td>
<td>0.3</td>
<td>1.0</td>
</tr>
<tr>
<td>Variability of Ball Release Speed (m·s⁻¹)</td>
<td>13</td>
<td>0.7 ± 0.1</td>
<td>0.7 ± 0.2</td>
<td>0.739</td>
<td>0.1</td>
<td>15.6</td>
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<tr>
<td>Mean Radial Error (cm)</td>
<td>13</td>
<td>43.3 ± 7.5</td>
<td>41.3 ± 8.1</td>
<td>0.685</td>
<td>4.6</td>
<td>12.5</td>
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<tr>
<td>Bivariate Variable Error (cm)</td>
<td>13</td>
<td>40.0 ± 7.3</td>
<td>36.0 ± 7.3</td>
<td>0.434</td>
<td>5.6</td>
<td>15.3</td>
</tr>
<tr>
<td>Delivery Rating of Perceived Exertion (% of 100)</td>
<td>13</td>
<td>86.1 ± 5.2</td>
<td>86.7 ± 5.2</td>
<td>0.650</td>
<td>3.2</td>
<td>3.9</td>
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<tr>
<td><strong>Fast Bowling Kinematic Variables</strong></td>
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<td></td>
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<td></td>
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<tr>
<td>Approach Speed (m·s⁻¹)*</td>
<td>13</td>
<td>5.2 ± 0.7</td>
<td>5.1 ± 1.1</td>
<td>0.615</td>
<td>-</td>
<td>14.1</td>
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<tr>
<td>Delivery Step Length (m)</td>
<td>13</td>
<td>1.35 ± 0.22</td>
<td>1.35 ± 0.24</td>
<td>0.983</td>
<td>0.03</td>
<td>2.7</td>
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<tr>
<td>Front-Knee Angle at Front Foot Contact (°)</td>
<td>8</td>
<td>157.4 ± 4.1</td>
<td>157.3 ± 3.0</td>
<td>0.849</td>
<td>1.7</td>
<td>1.1</td>
</tr>
<tr>
<td>Front-Knee Angle at Ball Release (°)</td>
<td>12</td>
<td>149.9 ± 21.0</td>
<td>148.6 ± 20.4</td>
<td>0.991</td>
<td>2.2</td>
<td>1.5</td>
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<tr>
<td>Event</td>
<td>Sample Size</td>
<td>Mean</td>
<td>SD</td>
<td>ICC</td>
<td>SEM</td>
<td>CV</td>
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<td>--------------------------------------------</td>
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<td>------------</td>
<td>-----------</td>
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<tr>
<td>Back Foot Contact to Front Foot Contact</td>
<td>13</td>
<td>0.21 ± 0.03</td>
<td>0.21 ± 0.03</td>
<td>0.971</td>
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<td>Duration (s)</td>
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<td></td>
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<tr>
<td>Front Foot Contact to Ball Release</td>
<td>13</td>
<td>0.13 ± 0.02</td>
<td>0.13 ± 0.02</td>
<td>0.966</td>
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<tr>
<td>Duration (s)</td>
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</tbody>
</table>

SD = standard deviation; ICC = intraclass correlation coefficient; SEM = standard error of measurement; CV = coefficient of variation; *SEM not calculated as approach speed data did not fit the normal distribution.
Table 4. The relationships between selected physical qualities and fast bowling performance measures.

<table>
<thead>
<tr>
<th></th>
<th>Peak Ball Release Speed</th>
<th>Mean Ball Release Speed</th>
<th>Variability of Ball Release Speed</th>
<th>Mean Radial Error</th>
<th>Bivariate Variable Error</th>
</tr>
</thead>
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<tr>
<td></td>
<td>$n$</td>
<td>$r_s$</td>
<td>$n$</td>
<td>$r_s$</td>
<td>$n$</td>
</tr>
<tr>
<td>Reach Height</td>
<td>29</td>
<td>-0.16</td>
<td>29</td>
<td>-0.07</td>
<td>29</td>
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<tr>
<td>3-RM Half Squat</td>
<td>30</td>
<td>0.08</td>
<td>30</td>
<td>0.14</td>
<td>30</td>
</tr>
<tr>
<td>3-RM Bench Press</td>
<td>26</td>
<td>0.28</td>
<td>26</td>
<td>0.29</td>
<td>26</td>
</tr>
<tr>
<td>1-RM Pull-Up</td>
<td>24</td>
<td>0.56**</td>
<td>24</td>
<td>0.56**</td>
<td>24</td>
</tr>
<tr>
<td>Predicted $\hat{\dot{V}}O_2$max</td>
<td>27</td>
<td>0.11</td>
<td>27</td>
<td>0.09</td>
<td>27</td>
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<tr>
<td>10-m Sprint</td>
<td>28</td>
<td>-0.35</td>
<td>28</td>
<td>-0.31</td>
<td>28</td>
</tr>
<tr>
<td>20-m Sprint</td>
<td>30</td>
<td>-0.42*</td>
<td>30</td>
<td>-0.37*</td>
<td>30</td>
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<tr>
<td>Total Time of 10 × 20-m Sprints</td>
<td>21</td>
<td>-0.35</td>
<td>21</td>
<td>-0.23</td>
<td>21</td>
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<tr>
<td>Reactive Strength Index</td>
<td>30</td>
<td>0.07</td>
<td>30</td>
<td>-0.05</td>
<td>30</td>
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<tr>
<td>Peak Height of 3 CMJs</td>
<td>28</td>
<td>0.21</td>
<td>28</td>
<td>0.18</td>
<td>28</td>
</tr>
<tr>
<td>Mean Height of 20 CMJs</td>
<td>27</td>
<td>0.29</td>
<td>27</td>
<td>0.23</td>
<td>27</td>
</tr>
<tr>
<td>Activity</td>
<td>Mean 1</td>
<td>SD 1</td>
<td>Mean 2</td>
<td>SD 2</td>
<td>Mean 3</td>
</tr>
<tr>
<td>-----------------------------------------------</td>
<td>--------</td>
<td>------</td>
<td>--------</td>
<td>------</td>
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</tr>
<tr>
<td>Best CPP of 3 CMJs</td>
<td>28</td>
<td>0.13</td>
<td>28</td>
<td>0.25</td>
<td>28</td>
</tr>
<tr>
<td>Mean CPP of 20 CMJs</td>
<td>27</td>
<td>0.21</td>
<td>27</td>
<td>0.34</td>
<td>27</td>
</tr>
<tr>
<td>Peak Height of 3 BPTs</td>
<td>29</td>
<td>0.27</td>
<td>29</td>
<td>0.18</td>
<td>29</td>
</tr>
<tr>
<td>Mean Height of 20 BPTs</td>
<td>28</td>
<td>0.34</td>
<td>28</td>
<td>0.25</td>
<td>28</td>
</tr>
<tr>
<td>Side Plank on Bowling Arm</td>
<td>28</td>
<td>-0.10</td>
<td>28</td>
<td>-0.09</td>
<td>28</td>
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<tr>
<td>Side Plank on Non Bowling Arm</td>
<td>30</td>
<td>0.02</td>
<td>30</td>
<td>0.07</td>
<td>30</td>
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<tr>
<td>Plank</td>
<td>30</td>
<td>0.17</td>
<td>30</td>
<td>0.10</td>
<td>30</td>
</tr>
<tr>
<td>Active Straight Leg Raise on Bowling Front Leg</td>
<td>29</td>
<td>0.17</td>
<td>29</td>
<td>0.32</td>
<td>29</td>
</tr>
<tr>
<td>Shoulder Horizontal Abduction on Bowling Arm</td>
<td>27</td>
<td>0.28</td>
<td>27</td>
<td>0.22</td>
<td>27</td>
</tr>
</tbody>
</table>

RM = repetition maximum; CMJ = countermovement jump; CPP = concentric peak power; BPT = bench press throw. *Denotes significance at \( p < 0.05 \). **Denotes significance at \( p < 0.01 \).
### Table 5. The relationships between selected physical qualities and fast bowling kinematic measures.

<table>
<thead>
<tr>
<th></th>
<th>Approach Speed</th>
<th>Delivery Step Length</th>
<th>Front-Knee Foot Contact to Front Foot Duration</th>
<th>Front-Knee Angle at Front Release to Ball Release Duration</th>
<th>Front-Knee Angle at Ball Release</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( n )</td>
<td>( r_s )</td>
<td>( n )</td>
<td>( r_s )</td>
<td>( n )</td>
</tr>
<tr>
<td>Reach Height</td>
<td>29</td>
<td>-0.14</td>
<td>29</td>
<td>-0.07</td>
<td>20</td>
</tr>
<tr>
<td>3-RM Half Squat</td>
<td>30</td>
<td>0.06</td>
<td>30</td>
<td>0.29</td>
<td>20</td>
</tr>
<tr>
<td>3-RM Bench Press</td>
<td>26</td>
<td>0.41*</td>
<td>26</td>
<td>0.11</td>
<td>18</td>
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<tr>
<td>1-RM Pull-Up</td>
<td>24</td>
<td>0.24</td>
<td>24</td>
<td>0.37</td>
<td>16</td>
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<tr>
<td>Predicted ( \dot{V}O_{2\text{max}} )</td>
<td>27</td>
<td>0.10</td>
<td>27</td>
<td>-0.02</td>
<td>18</td>
</tr>
<tr>
<td>10-m Sprint</td>
<td>28</td>
<td>0.01</td>
<td>28</td>
<td>-0.23</td>
<td>19</td>
</tr>
<tr>
<td>20-m Sprint</td>
<td>30</td>
<td>-0.15</td>
<td>30</td>
<td>-0.28</td>
<td>21</td>
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<tr>
<td>Total Time of 10 × 20-m Sprints</td>
<td>21</td>
<td>0.05</td>
<td>21</td>
<td>-0.26</td>
<td>14</td>
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<tr>
<td>Reactive Strength Index</td>
<td>30</td>
<td>0.08</td>
<td>30</td>
<td>0.11</td>
<td>20</td>
</tr>
<tr>
<td>Peak Height of 3 CMJs</td>
<td>28</td>
<td>0.06</td>
<td>28</td>
<td>0.25</td>
<td>20</td>
</tr>
<tr>
<td>Test Description</td>
<td>Mean Height of 20 CMJs</td>
<td>Best CPP of 3 CMJs</td>
<td>Mean CPP of 20 CMJs</td>
<td>Peak Height of 3 BPTs</td>
<td>Mean Height of 20 BPTs</td>
</tr>
<tr>
<td>-----------------------------------------------</td>
<td>------------------------</td>
<td>--------------------</td>
<td>---------------------</td>
<td>----------------------</td>
<td>------------------------</td>
</tr>
<tr>
<td></td>
<td>27 0.18 27 0.24 19 -0.17 23 -0.10 27 -0.21 27 -0.21</td>
<td>28 0.17 28 0.24 20 -0.17 24 -0.12 28 0.03 28 0.12</td>
<td>27 0.09 27 0.26 19 -0.32 23 -0.11 27 0.08 27 0.18</td>
<td>29 0.20 29 0.06 20 -0.29 25 -0.07 29 -0.13 29 0.11</td>
<td>28 0.16 28 0.02 19 -0.57* 24 -0.07 28 -0.20 28 0.14</td>
</tr>
</tbody>
</table>

RM = repetition maximum; CMJ = countermovement jump; CPP = concentric peak power; BPT = bench press throw. *Denotes significance at $p < 0.05$. **Denotes significance at $p < 0.01$. 

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16

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Table 6. The relationships between selected fast bowling kinematic variables and fast bowling performance measures.

<table>
<thead>
<tr>
<th></th>
<th>Peak Ball Release Speed</th>
<th>Mean Ball Release Speed</th>
<th>Variability of Ball Release Speed</th>
<th>Mean Radial Error</th>
<th>Bivariate Variable Error</th>
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<tbody>
<tr>
<td></td>
<td>$n$</td>
<td>$r_s$</td>
<td>$n$</td>
<td>$r_s$</td>
<td>$n$</td>
</tr>
<tr>
<td>Approach Speed</td>
<td>31</td>
<td>0.15</td>
<td>31</td>
<td>0.26</td>
<td>31</td>
</tr>
<tr>
<td>Delivery Step Length</td>
<td>31</td>
<td>0.49**</td>
<td>31</td>
<td>0.51**</td>
<td>31</td>
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<tr>
<td>Front-Knee Angle at Front Foot Contact</td>
<td>21</td>
<td>&lt; -0.01</td>
<td>21</td>
<td>0.13</td>
<td>21</td>
</tr>
<tr>
<td>Front-Knee Angle at Ball Release</td>
<td>27</td>
<td>0.10</td>
<td>27</td>
<td>0.07</td>
<td>27</td>
</tr>
<tr>
<td>Back Foot Contact to Front Foot Contact Duration</td>
<td>31</td>
<td>-0.05</td>
<td>31</td>
<td>0.02</td>
<td>31</td>
</tr>
<tr>
<td>Front Foot Contact to Ball Release Duration</td>
<td>31</td>
<td>-0.44*</td>
<td>31</td>
<td>-0.45*</td>
<td>31</td>
</tr>
</tbody>
</table>

*Denotes significance at $p < 0.05$. **Denotes significance at $p < 0.01$. 