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ABSTRACT

The ability of a batsman to clear the boundary is a major contributor to success in modern cricket. The aim of this study was to identify technique parameters characterising those batsmen able to generate greater bat speeds, ball launch speeds, and carry distances during a range hitting task in cricket. Kinematic data were collected for 20 batsmen ranging from international to club standard, and a series of ball launch, bat-ball impact, and technique parameters were calculated for each trial. A stepwise multiple linear regression analysis found impact location on the bat face in the medio-lateral and longitudinal directions and bat speed at impact to explain 68% of the observed variation in instantaneous post-impact ball speed. A further regression analysis found the X-factor (separation between the pelvis and thorax segments in the transverse plane) at the commencement of the downswing, lead elbow extension, and wrist uncocking during the downswing to explain 78% of the observed variation in maximum bat speed during the downswing. These findings indicate that players and coaches should focus on generating central impacts with the highest possible bat speed. Training and conditioning programmes should be developed to improve the important kinematic parameters shown to generate greater bat speeds, particularly focussing on increased pelvis to upper thorax separation in the transverse plane.

Keywords: kinematics; power; X-factor

INTRODUCTION

The ability of a batsman to clear the boundary is a major contributor to batting success in modern cricket, and as such is frequently practiced during cricket training. Indeed, winning teams in the 2008 Indian Premier League T20 competition hit 20% more sixes, 14% more fours and scored 5% less singles than the non-winning team (Petersen et al., 2008). Additionally, the percentage of runs in one day internationals obtained by clearing the boundary has gradually increased from 5.9% in 1983 to 8.7% in 2013 (Narayanan, 2013). To date no studies have investigated the technical aspects of range hitting (batting for maximal ball carry distance) in cricket, with the majority of research focused on establishing the mechanics of the front foot drive (Elliott et al., 1993; Stretch et al., 1998; Stuelcken et al., 2005; Taliep et al., 2007), or identifying differences in technique when facing different delivery methods (Gibson & Adams, 1989; Renshaw et al., 2007; Cork et al., 2010; Pinder et al., 2011; Peploe et al., 2014). While participants executing the front foot drive in previous studies conceivably placed their primary focus on control and precision in striking the ball along the floor, during range hitting players strive for maximum ball carry distance and launch speed with little emphasis on placement. This key difference likely creates substantial kinematic differences between the two shots, and as such the techniques used by batsmen when range hitting are not fully understood in a research context.

Several studies have investigated the optimal launch characteristics across a range of sports including baseball (Watts & Baroni, 1989; Sawicki et al, 2001), shot put (Linthorne, 2001), and the soccer throw in (Linthorne & Everett, 2006). In general, these studies have identified an optimal vertical launch angle for maximum carry distance, dependent on the launch speed, release height, and aerodynamic properties of the projectile in question. Strong relationships have been identified in cricket between the impact location of the ball on the bat face and ball launch speed (Peploe et al., 2018), with impacts just 2 cm off-centre in the medio-lateral direction causing a 6% reduction in ball speed. In golf, higher clubhead velocities have also been linked to greater ball launch speed (Chu et al., 2010) and driving distances (Hume et al., 2005; Gordon et al., 2009). The effects of bat-ball impact characteristics on post-impact ball speed and direction in range hitting are unlikely to differ to previous research.

Despite the limited research into batting kinematics, a number of studies have investigated the technical factors important to the generation of equipment and ball speed in other sports. In golf, a large angular separation between the pelvis and upper thorax in the transverse plane (often referred to as the X-factor; Mclean, 1992) at the top of the backswing and during the downswing, has been strongly linked to increased clubhead speed (Cheetham et al., 2001; Myers et al., 2008; Zheng et al., 2008; Chu et al., 2010). The 2D separation angle in the transverse plane and angular velocity of the pelvis and thorax segments have also been identified as important factors for generating bat and ball speed in baseball hitting (Escamilla et al., 2009), the forehand smash in badminton (Zhang et al., 2016), and the tennis forehand (Landlinger et al., 2010; Seeley et al., 2011).

Low-handicap golfers have been shown to employ a greater and quicker weight shift towards the rear (most posterior in the stance) foot during the backswing, then forwards towards the lead (most anterior in the stance) foot in the downswing, (Wallace et al., 1990; Koenig et al., 1994; Chu et al., 2010). Professional (Welch et al., 1995) and skilled (Escamilla et al., 2009) baseball players were also found to spend more time in the stride phase (between the commencement and completion of the forward stride) 'loading up' in preparation for the downswing than their lesser skilled counterparts, and exhibited lead knee extension in the approach to impact. This increased linear momentum and extension of the lead knee may allow additional kinetic energy to be generated in the lower body and trunk, and more efficiently transferred to the upper extremities. Finally, an increased cocking and uncocking of the wrists (the angle formed between the club/bat and the lead forearm), and extension of the lead elbow has also been linked to golf clubhead and baseball bat speed (Robinson, 1994; Sprigings & Neal, 2000; Zheng et al., 2008; Escamilla et al., 2009; Chu et al., 2010).

Ball speed and vertical launch angle are the primary determinants of carry distance and are fundamentally related to bat speed and bat angle at impact, amongst other factors. Although several studies have addressed the link between various kinematic technique parameters and equipment speed in other sports, no such research has been conducted in cricket batting. Further investigation of these primary outcome measures and the kinematic factors important to each will allow athletes, coaches, and researchers a greater understanding of the mechanisms and techniques related to success, and guide the design of more specific and targeted training programmes for range hitting.

Whilst central impacts on the bat face are likely of high importance, it is also useful to discover what players can do to maximise carry distance when the timing and impact location of the swing are already good. Range hitting in cricket typically combines similar upper body mechanics to a golf swing, with a forward stride towards an incoming ball as exhibited by baseball hitters. Given the importance of a greater X-factor in golf (Cheetham et al., 2001; Myers et al., 2008; Zheng et al., 2008; Chu et al., 2010), as well as greater pelvis and thorax angular velocity in baseball hitting (Escamilla et al., 2009) and the tennis forehand (Landlinger et al., 2010; Seeley et al., 2011), the motion of the pelvis and thorax in the transverse plane may also predict bat speed in cricket range hitting.

When considering lower body kinematics, the forward stride and relatively known nature (arrival location and speed) of ball delivery from the bowling machine in this study is representative of baseball, with the primary difference being the ball bounce before impact. As such it may be expected that successful hitters in cricket are more likely to employ the longer stride phase exhibited by skilled baseball players (Welch et al., 1995; Escamilla et al., 2009), than the greater and faster weight shift between feet used by skilled golfers (Wallace et al., 1990; Koenig et al., 1994; Chu et al., 2010). Although similarities in lower body kinematics are present between the tennis forehand and range hitting in cricket, the primary focus on ball velocity and carry distance in cricket, compared to the control and topspin requirements in the tennis forehand, likely cause substantial differences in approach and make comparisons with baseball and golf more appropriate. Likewise, the forehand smash in badminton (Zhang et al., 2016) is an overhead technique and thus differs in technique from cricket range hitting.

The aim of this study was to identify the key kinematic, bat-ball impact, and launch parameters that best predict bat speed, ball launch speed, and carry distance during a range hitting task in cricket. This will provide valuable information to players and coaches in the development of more effective hitting techniques and training methods, and form a basis for the continued assessment of the mechanics of generating high ball launch and bat speeds in cricket batting.

It is firstly hypothesised that central impacts on the bat face and greater bat speeds will predict greater post-impact ball speeds. It is secondly hypothesised that vertical ball launch angle will vary as a function of the bat angle about the global medio-lateral axis at the time of impact. Thirdly, a greater X-factor at the top of the backswing and during the downswing are hypothesised to generate faster bat speeds. If the findings of this study are to be practically applicable when considering progression in range hitting ability, then it is important that variables contributing to the difference between batters ranging from amateur to international level are identified. This necessitates the recruitment of a heterogeneous ability range to the sample population such that the effects of variation in each of the kinematic variables can be observed.

METHODS

All testing was conducted at the England & Wales Cricket Board National Cricket Performance Centre in Loughborough, UK, on an indoor standard sized artificial cricket pitch. Kinematic data was recorded using an 18 camera Vicon Motion Analysis System (OMG Plc, Oxford, UK) operating at 250 Hz. Testing procedures were explained to each participant, and informed written consent was obtained in accordance with the guidelines of the Loughborough University Ethical Advisory Committee. All participants completed a self-selected warm-up and a series of familiarisation trials of the range hitting task under equivalent testing conditions immediately prior to data collection.

Data Collection

Twenty male cricket batsmen (22.5 ± 3.1 years, 1.82 ± 0.04 m, 80.0 ± 7.8 kg) participated in this investigation. Participants with large variation in range hitting experience and ability were selected so as to ensure a range of performances and not to distort the importance of individual variables. Participants included three international batsmen (England / England Lions), nine county batsmen including six who had represented England under 19's, five premiership club batsmen, and three club batsmen. Forty-six 14 mm retro-reflective markers were attached to each batsman (Figure 1), positioned over or on padding adjacent to bony landmarks. An additional five markers were positioned on the bat (Figure 1), as well as five 15 x 15 mm patches of 3M Scotch-Lite reflective tape placed on the ball (Figure 2).

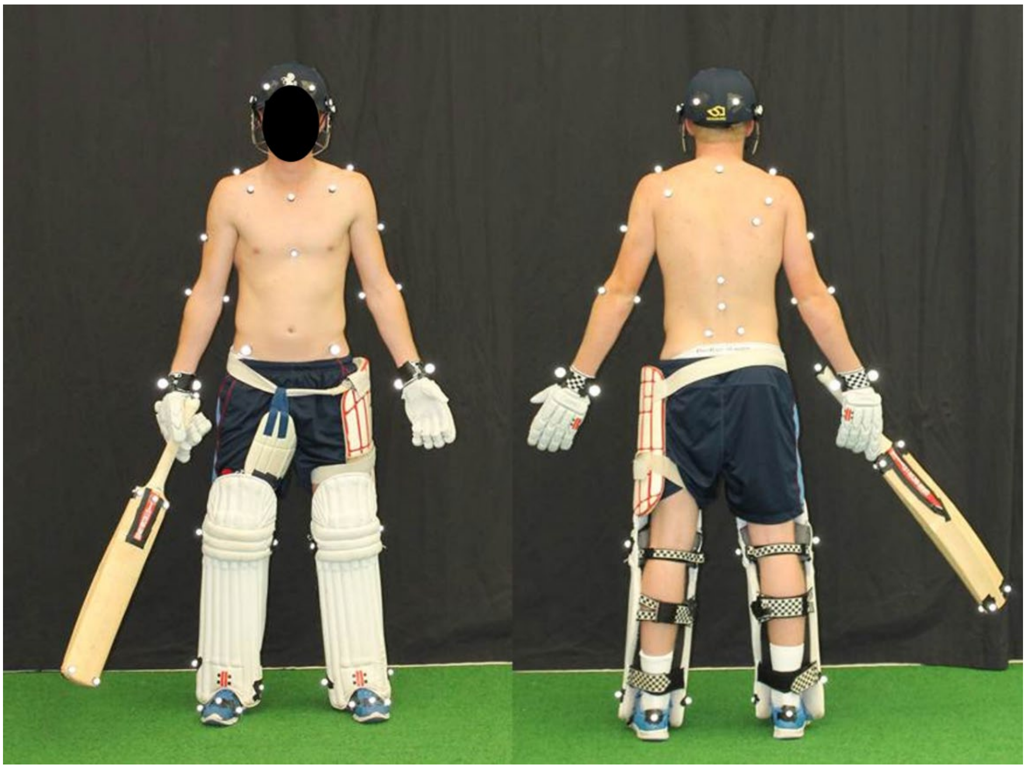

Figure 1. Full body and bat marker set used for motion capture trials.

Figure 2. Reflective tape positioned on the cricket ball.

Each participant performed a series of shots (14 ± 4) against a bowling machine (BOLA Professional; release speed 32.3 ms^{-1}), aiming to hit the ball for maximum carry distance straight back over the bowling machine in the same manner that they would attempt in a match, and thus standardising the shots played by each participant. The bowling machine was directed towards a full length suitable for the shot. Resultant inbound ball speed on the approach to impact (after ball bounce) was 25.0 ± 1.3 ms^{-1}. Each participant used their own bat throughout the data collection. This ensured familiarity for the participants, as the altered inertial properties of a standardised bat would have affected the kinematics of the shot. Previous work has shown little difference in batted ball speed for a given impact location, or impact location-ball speed relationship between different bats (Symes, 2006; Peploe et al., 2018). Only trials where the ball was projected forwards in the anterior-posterior direction (towards the bowling machine) post-impact were selected for analysis (n = 239; 12 ± 2 trials per participant).

Data Reduction

Batting trials were labelled within Vicon Nexus software (OMG Plc, Oxford, UK). Trajectories were filtered using a recursive two-way Butterworth low-pass filter with a cut-off frequency of 15 Hz, determined via residual analysis (Winter, 2009). Local coordinate systems were defined in Visual 3D software (C-Motion Inc., Germantown, MD, USA), forming a three-dimensional 14 segment model of a batsman (head and neck, thorax, pelvis, 2 × upper arm, 2 × forearm, 2 × thigh, 2 × shank, 2 × foot, and bat). Coordinate systems were defined using three markers on the segment itself, allowing segment orientations and joint angles to be calculated. The z-axis pointed superiorly along the longitudinal axis of the segment, the x-axis pointed toward the participant's right, and the y-axis pointed anteriorly.

The ankle, knee, shoulder, elbow, and wrist joint centres were defined as being the midpoint of pairs of markers placed across the joint. A rigid link was assumed between the top hand (left hand for a right-handed batsman) and bat (Tsunoda et al., 2004; Stuelcken et al., 2005), assuming a fixed grip with all bat rotation occurring about the wrist rather than the hand. The effects of this assumption were assessed to be negligible. The wrist cocking angle was calculated via the movement of the bat relative to the lead forearm segment. The hip joint centres were calculated from markers placed over the left and right anterior and posterior superior iliac spines (Bell et al., 1989). Motion of the thorax segment was defined using markers placed over the superior and inferior ends of the sternum, as well as the spinous processes of L1, T10 and C7 (Worthington et al., 2013). Joint angles were calculated as Cardan angles using an x-y-z sequence, corresponding to flexion-extension, abduction-adduction, and longitudinal rotation, respectively. Rotations of the pelvis and thorax segments were calculated relative to the global coordinate system using a z-y-x Cardan sequence (Baker, 2001) to minimise errors as a result of pelvic tilt or lateral rotation. Whole body centre of mass (COM) location was computed from the segment geometry and relative masses (Hanavan, 1964).

Events corresponding to the commencement of the downswing (DS), start (SS) and end (SE) of the forward stride, and the time of bat-ball impact (IMP) were identified for each trial from the kinematic data (Peploe et al., 2014). IMP was identified from a change in the anterior-posterior ball centre direction. DS was defined as the frame at which the angular velocity of the bat about the global medio-lateral axis changed from backwards to forwards rotation prior to impact. SS was defined as the time at which the lead foot segment's linear velocity passed above a threshold level of 0.1 ms^{-1} in the global anterior-posterior direction. SE was defined as the point at which the lead foot segment's linear and angular velocity passed below threshold levels of 0.1 ms^{-1} in the global anterior-posterior direction and 0.1°s^{-1} forwards about the foot's local medio-lateral axis respectively, following the commencement of the forward stride. This represented the time at which the foot was flat on the floor rather than the time of first contact.

The single ball displacement equation methodology of Peploe et al. (2017) was used to determine the impact location relative to the sweetspot (17.5 cm from the toe along the midline of the bat; Bower, 2012; Peploe et al., 2018) in the X (medio-lateral) and Z (longitudinal) directions on the bat, resultant post-impact ball speed, and vertical ball launch angle for each trial. Vertical ball launch angle was calculated from vertical and anterior-posterior instantaneous post-impact ball velocities. Ball carry distance was calculated from resultant instantaneous post-impact ball speed and vertical launch angle using a validated iterative ball flight model accounting for gravity and air resistance (Peploe, 2016). The maximum resultant bat distal endpoint speed during the downswing and at impact were determined from the midpoint of the two distal bat blade markers. The vertical and medio-lateral normality of each impact was defined as the two-dimensional angular difference between the inbound ball trajectory (calculated over a 40 ms interval prior to impact) and a vector normal to the bat face. The mass of each participant's bat was measured using clinical scales, and COM location was determined in the longitudinal direction using a balance test.

Twenty-eight further kinematic parameters were also calculated for each trial (Table 1), describing elements of technique associated with increased bat or clubhead speed in other hitting sports, or that are thought to be important by elite coaches.

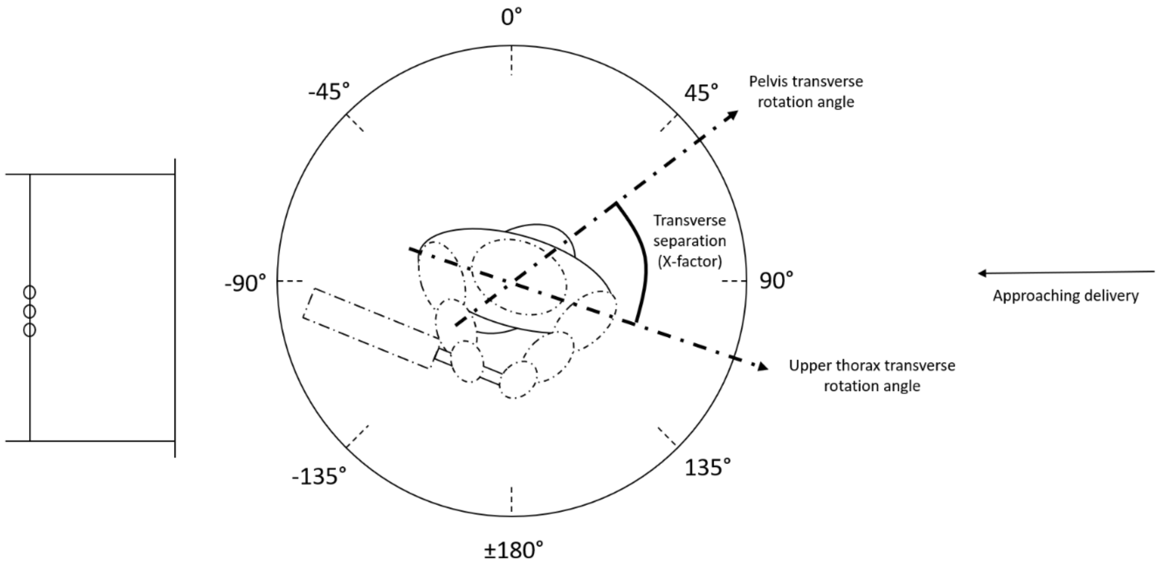

Figure 3. Definition of the pelvis and upper thorax transverse rotation, and separation (X-factor) angles measured.

Table 1. Kinematic parameters and definitions.

Parameter	Definition
Bat angle DS / IMP	The angular rotation of the bat about the global medio-lateral axis (corresponding to the primary axis of rotation during the swing)
Bat angular rotation (DS to IMP)	The change in bat angle about the global medio-lateral axis during the downswing
Bat COM height DS	The height of the bat centre of mass in the global vertical direction
Wrist cocking angle DS / IMP	The angular offset between the lead forearm and the bat corresponding to abduction/adduction at the wrist joint
Wrist uncocking (min to IMP)	The change in wrist cocking angle between its minimum value during the downswing and bat-ball impact
Lead/rear elbow angle DS / IMP	The anatomical flexion/extension angle of the lead/rear elbow (straight = 180°, flexed < 180°)
Lead/rear elbow extension (DS to IMP)	The change in lead/rear elbow angle between its minimum value during the downswing and bat-ball impact
Pelvis angle Z IMP	The angle of the pelvis segment about the global vertical axis (corresponding to transverse rotation)
Thorax angle Z IMP	The angle of the thorax segment about the global vertical axis (corresponding to transverse rotation)
X-factor DS	The angular separation between the pelvis and thorax segments in the transverse plane (Figure 3)
X’-factor DS	The angular separation between the pelvis and thorax segments in the frontal plane
Max X-factor (DS to IMP)	The maximum X-factor during the downswing
Max X’-factor (DS to IMP)	The maximum X’-factor during the downswing
X-factor stretch	The change in X-factor between the start of the downswing and its maximum value prior to bat-ball impact
X-factor reduction (max to IMP)	The change in X-factor between its maximum value and the time of bat-ball impact
X’-factor reduction (max to IMP)	The change in X’-factor between its maximum value and the time of bat-ball impact
COM displacement Y (min to IMP)	The displacement of the whole body centre of mass in the global anterior-posterior direction between its minimum value and the time of bat-ball impact
Lead knee angle IMP	The anatomical flexion/extension angle of the lead knee (straight = 180°, flexed < 180°)
Lead knee extension (SE to IMP)	The change in lead knee angle between the end of the forward stride and the time of bat-ball impact
Base length IMP	The resultant distance between the centres of mass of the left and right feet
Base length (% height) IMP	The above value as a percentage of the batsman’s height

Note: DS = commencement of the downswing, SE = end of the forward stride, IMP = time of bat-ball impact, COM = centre of mass.

Data Analysis

All statistical analyses were performed within SPSS v.23 (IBM Corporation, Armonk, NY, USA). To identify which of the bat-ball impact and launch parameters (Table 2) best explained the variation in ball launch speed, a forwards stepwise linear regression incorporating all trials hit in the anterior direction (n = 239) was conducted. This ensured that the effects of successful and unsuccessful shot timings and hence impact locations on the bat face were included in the regression analysis. A second forward stepwise linear regression incorporating the same trials was then conducted to explain the variation in vertical ball launch angle, although the resulting model (containing bat angle about the global medio-lateral axis and impact location in the medio-lateral direction of the bat) did not meet the assumption of normal standardised residuals. As such a third forward stepwise linear regression was conducted and presented, incorporating only those trials with impacts occurring within 2 cm of the midline of the bat (n = 99; representing the 'sweet region' in the medio-lateral direction; Peploe et al., 2018). This was intended to remove any effect caused by off-centre impacts and isolate the influence of other bat-ball impact and launch parameters. A Pearson product moment correlation was also conducted (with $P < 0.05$ indicating significance) between launch angle and speed.

The three best trials in terms of ball launch speed were then identified for each participant and averaged for each kinematic parameter to provide representative data for each batsman (Chu et al., 2010; Worthington et al., 2013). To identify which of the kinematic parameters best explained the variation in maximum bat speed during the downswing, a further forward stepwise linear regression, with a maximum of four parameters included in the predictive equation (Tabachnick & Fidell, 2007), was conducted. Due to the confounding effects of swing timing on bat speed at impact, regardless of kinematic parameters, maximum bat speed during the downswing was assessed as the dependent variable.

Pearson Product Moment correlation was used to establish relationships throughout all analyses, with a P-value < 0.05 indicating statistical significance. Only parameters significantly correlated with the dependent variable were put forward into each regression analysis. The requirement for the inclusion of a parameter in the regression equations was $P < 0.05$. Regression models were rejected if coefficient 95% confidence intervals included zero or if correlations, tolerance statistics, or variance inflation factors showed evidence of multicollinearity (Bowerman & O'Connell, 1990; Myers, 1990; Menard, 1995; Draper & Smith, 1998; Field, 2013). Regression models were also rejected if two fundamentally related parameters (such as a joint angle at one instant and the change in the same joint angle between that same instant and another) were included. The assumption of independent errors was checked using the Durbin-Watson statistic (Field, 2013). Normality of the standardised residuals in the regression models was confirmed via observation of a histogram and normal P-P plot (Field, 2013), and Shapiro-Wilk tests. P-values for the three regression models presented ranged from 0.48 to 0.61 indicating no evidence against the assumption of normality of the residuals. The percentage of variation in the dependent variable explained by the independent variables in each regression was determined by Wherry's (1931) adjusted R^2 value. To overcome the potential limitation of stepwise regressions relying on a single best model, the explained variation for all possible regressions with the same number of parameters as the stepwise solution were determined for comparison.

RESULTS

The 239 trials selected for initial analysis had a substantial range of carry distances of 3.5 – 101.5 m (mean 52.1 ± 19.6 m) and a wide range of bat-ball impact and launch parameters. The trials selected for kinematic analysis (the three greatest ball launch speeds for each participant; n = 60) had larger carry distances (mean 64.2 ± 19.7 m) and a narrower range of bat-ball impact and launch parameters (Table 2). For each playing standard, average carry distances and ball launch speeds for all trials and for those trials selected for kinematic analysis are displayed in Table 3. For the three trials selected for kinematic analysis per participant, the mean intra-participant standard deviation for carry distance and ball launch speed were 15.8 m and 1.7 ms-1 for international players, 12.5 m and 1.4 ms-1 for county and England Under 19 players, 25.0 m and 1.8 ms-1 for premiership club players, and 15.5 m and 1.6 ms-1 for club players.

Table 2. Summary of launch and bat-ball impact parameters (mean ± SD) for all trials and central impacts (within 2 cm of the midline of the bat) only.

Parameter	All trials	Central impacts
Vertical ball launch angle (°)	37.5 ± 20.4	28.3 ± 14.5
Ball launch speed (ms^{-1})	28.1 ± 4.1	32.3 ± 2.5
Maximum bat speed (ms^{-1})	27.0 ± 2.3	27.5 ± 2.0
Bat speed at impact (ms^{-1})	26.8 ± 2.3	27.3 ± 2.0
Normality of impact vertical (°)	21.8 ± 15.6	19.5 ± 13.0
Normality of impact medio-lateral (°)	3.0 ± 15.1	0.5 ± 12.1
Bat angle X IMP (°)	11.5 ± 15.2	9.4 ± 13.2
Bat mass (kg)	1.11 ± 0.07	1.11 ± 0.07

Note: X = about the global medio-lateral axis, IMP = time of bat-ball impact.

Table 3. Carry distances and ball launch speeds for each playing standard.

	All Trials		Fastest Three Trials	
Standard	Carry Distance (m)	Ball Launch Speed (ms^{-1})	Carry Distance (m)	Ball Launch Speed (ms^{-1})
International	52.1 ± 24.0	29.5 ± 4.5	72.3 ± 15.8	34.5 ± 1.7
County / England Under 19	56.4 ± 18.4	29.0 ± 3.4	68.8 ± 12.5	32.6 ± 1.4
Premiership Club	52.4 ± 17.4	27.5 ± 3.5	57.6 ± 24.9	31.6 ± 1.8
Club	43.5 ± 15.0	25.5 ± 3.1	53.6 ± 15.5	30.0 ± 1.6

The best individual predictor of ball launch speed was the distance of ball impact from the estimated sweetspot of the bat in the medio-lateral direction, explaining 30.1% of the variation in ball launch speed (SEE = 3.45 ms-1). The inclusion of bat speed at impact, and impact location in the longitudinal direction, increased the total explained variation in ball launch speed to 67.6% (SEE = 2.35 ms-1; Table 4). Trials with an impact location nearer the sweetspot in both the medio-lateral and longitudinal directions, and with a higher pre-impact bat speed, were found to produce a higher ball launch speed.

Table 4. Stepwise linear regression equations predicting ball launch speed for all trials.

			95% confidence intervals			
Model	Parameter	Coefficient	Lower bound	Upper bound	P	Percentage explained
1	Impact location X	-111.965	-133.65	-90.28	< 0.001	30.1
	Constant	31.364	30.59	32.14	< 0.001	
2	Impact location X	-115.865	-133.38	-98.35	< 0.001	54.5
	Bat speed IMP	0.883	0.73	1.04	< 0.001	
	Constant	7.799	3.65	11.95	< 0.001	
3	Impact location X	-109.693	-124.51	-94.88	< 0.001	67.6
	Bat speed IMP	0.772	0.64	0.90	< 0.001	
	Impact location Z	-35.584	-42.70	-28.47	< 0.001	
	Constant	12.587	8.96	16.22	< 0.001	

Note: X = medio-laterally on the bat face, Z = longitudinally on the bat face, IMP = time of bat-ball impact.

The best predictor of vertical ball launch angle for the regression model incorporating only central impacts was the bat angle about the global medio-lateral axis at impact, explaining 82.6% of the variation (SEE = 6.5°; Table 5). No other launch or bat-ball impact parameters were included in this regression model. Trials with a bat angle further forward beyond vertically downwards about the global medio-lateral axis at impact were found to produce higher ball launch angles. A weak negative correlation ($r = 0.249$, $p < 0.001$) was also found between launch angle and ball speed.

Table 5. Stepwise linear regression equations predicting ball launch speed for all trials.

			95% confidence intervals			
Model	Parameter	Coefficient	Lower bound	Upper bound	P	Percentage explained
1	Bat angle X IMP	0.954	0.87	1.04	< 0.001	82.6
	Constant	19.314	17.75	20.88	< 0.001	

Note: IMP = time of bat-ball impact.

The best individual kinematic predictor of bat speed was the angular separation of the pelvis and thorax segments in the transverse plane at the commencement of the downswing (X-factor DS), explaining 28.0% of the variation in bat speed (SEE = 1.65 ms-1). Inclusion of the magnitude of lead elbow extension and wrist uncocking during the downswing to the regression equation, increased the total explained variation in bat speed to 77.7% (SEE = 0.92 ms-1; Table 6; Figure 4). Participants who displayed a larger X-factor at the start of the downswing, and a greater magnitude of lead elbow extension and wrist uncocking during the downswing, were found to generate higher bat speeds.

Table 6. Stepwise linear regression equations predicting ball launch speed for all trials.

			95% confidence intervals			
Model	Parameter	Coefficient	Lower bound	Upper bound	P	Percentage explained
1	X-factor DS	0.147	0.04	0.25	< 0.001	28.0
	Constant	24.766	22.62	26.91	< 0.001	
2	X-factor DS	0.153	0.07	0.23	0.001	58.6
	Lead elbow ext.	0.088	0.04	0.14	0.001	
	Constant	22.493	20.43	24.56	< 0.001	
3	X-factor DS	0.147	0.09	0.21	< 0.001	77.7
	Lead elbow ext.	0.098	0.06	0.14	< 0.001	
	Wrist uncocking	0.087	0.04	0.13	0.001	
	Constant	17.920	15.03	20.81	< 0.001	

Note: DS = commencement of the downswing, ext. refers to extension of the lead elbow.

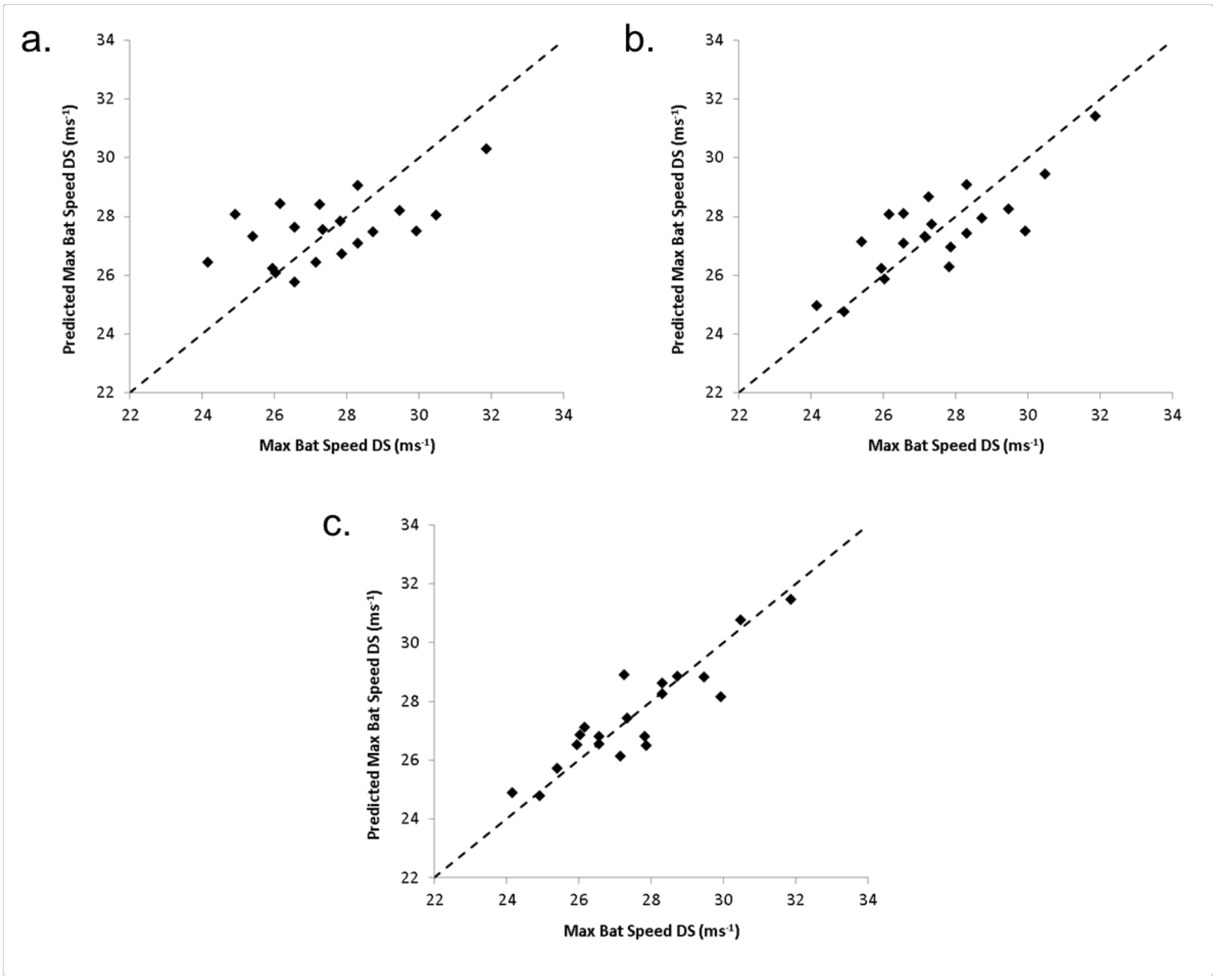

Figure 4. Predicted maximum bat speed against actual maximum bat speed for the one parameter (a), two parameter (b), and three parameter (c) linear regression models (Table 6). Dashed line y = x (predicted bat speed = actual bat speed).

DISCUSSION

The present study has identified the launch, bat-ball impact, and kinematic parameters that best explain the variation in carry distance, ball launch speed, vertical ball launch angle, and bat speed during a range hitting task in cricket. The participants hit carry distances ranging from 3.5 to 101.5 m (mean 52.1 ± 19.6 m). Three regression models accounted for 67.6% of the observed variation in ball launch speed, 82.5% of the variation in vertical ball launch angle, and 77.7% of the variation in maximum bat speed, suggesting that the most important factors in generating large carry distances have been identified.

Initial assessment of the launch parameters shows that, although the range of vertical launch angles observed in this study was large, in their three highest ball speed trials participants hit at angles (28.3 ± 14.5°) on average substantially below the optimum 42° (according to the flight model used in this study (Peploe, 2016)). While a weak negative correlation indicates that lower launch angles were associated with higher launch speeds, this could also suggest that players favour lower trajectories to minimise the risk of launching the ball too high, and thus giving fielders time to reposition for a catch. It is assumed in the present study that generating large carry distances represents success in range hitting, and it remains true that the parameters explaining variation in maximum bat speed would still be of importance if a player aimed at a slightly higher or lower than optimal launch angle.

Three parameters were found to explain 67.6% of the observed variation in ball launch speed: impact location in the medio-lateral and longitudinal directions, and bat speed at impact. This supports the present study's hypothesis that central impact locations on the bat face and faster bat speeds would generate faster ball launch speeds. The combined importance of impact location in the medio-lateral and longitudinal directions, together explaining 43.1% of the variation in ball launch speed, suggests that players who are consistently able to impact the ball close to the sweetspot of the bat are more likely to be successful than those who generate higher bat speeds without the required accuracy. This supports previous research in cricket (Symes, 2006; Bower, 2012; Peploe et al., 2018) and tennis (Elliott et al., 1980), indicating that off-centre impacts cause significant reductions in post-impact ball speed. However, for those players able to consistently generate impacts near the sweetspot, such as the elite batsmen included in this study, increasing bat speed at the point of impact becomes vital in producing higher ball launch speeds.

In the vertical ball launch angle regression model incorporating central impacts, unsurprisingly, and as hypothesised, the bat angle about the global medio-lateral axis at the time of impact was found to be the best predictor, explaining 82.5% of the observed variation. The bat angle at impact is most likely a function of the timing of the bat swing relative to the arrival time and position of the inbound ball and so players and coaches should prioritise developing correct timing of the swing. It is anticipated that impact location, particularly in the medio-lateral direction, has a non-linear multi-directional effect on vertical ball launch angle, with off-centre impacts being related to both higher and lower trajectories (Symes, 2006; Peploe et al., 2018) due to a combination of bat rotation about the longitudinal axis and the ball sliding up the bat face during impact. This is likely to have a more substantial effect on those trials towards the higher extreme of ball launch angle, and may explain the non-normality of residuals found in the regression model incorporating all trials.

As hypothesised, the best individual predictor of bat speed was the X-factor at the commencement of the downswing, explaining 28.0% of the observed variation. As previously found in golf (Myers et al., 2008; Chu et al., 2010), baseball hitting (Escamilla et al., 2009), and the tennis forehand (Landlinger et al., 2010) batsmen who displayed a larger angular separation between the pelvis and thorax segments in the transverse plane (with the pelvis rotated more front on towards the bowler) were found to generate higher bat speeds. This is thought to allow batsmen to make efficient use of the stretch-shortening cycle, stretching active muscles during eccentric loading to increase muscular force and power output during the final concentric phase of movement (Komi, 1984; 2000; Ettema et al., 2001), and leading to faster uncoiling during the downswing (Myers et al., 2008). Interestingly, the average maximum X-factor in the present study (25 ± 6°) was similar to those found in baseball hitting (19 ± 8°; Fleisig et al., 2013) and the tennis forehand (23 ± 8°; Landlinger et al., 2010; 30 ± 7°, Seeley et al., 2011), although substantially lower than in golf (62 ± 8°, Myers et al., 2008; 60 ± 7°, Zheng et al., 2008). The lower pre-impact separation recorded during these actions, including cricket batting, suggests a lower magnitude of pelvis and thorax axial rotation, perhaps because players are forced to react to the unpredictable nature of the ball arrival time and location.

The addition of lead elbow extension and wrist uncocking during the downswing into the regression model increased the total variation in bat speed explained to 77.7%. Batsmen who exhibited a greater magnitude of lead elbow extension and wrist uncocking during the downswing were found to generate higher bat speeds, supporting previous research in golf (Robinson, 1994; Sprigings & Neal, 2000; Chu et al., 2010) and baseball (Escamilla et al., 2009). Increased elbow extension and wrist uncocking will not only maximise the bat velocity, but also maximise the length of the bat-arm system at impact (Hume et al., 2005).

The importance of the angular separation between the pelvis and thorax segments in the transverse plane, as well as extension at the elbow and wrist uncocking adds to a growing body of similar findings in other hitting sports including golf and baseball (Robinson, 1994; Sprigings & Neal, 2000; Cheetham et al., 2001; Myers et al., 2008; Zheng et al., 2008; Escamilla et al., 2009; Chu et al., 2010). Cricket batsmen seeking to maximise bat speed and hence carry distance should aim to increase their pelvis-thorax angular separation at the commencement of the downswing, as well as subsequently increasing their magnitude of lead elbow extension and wrist uncocking during the downswing. It is of interest, however, that none of the measured lower body kinematic parameters were included in the regression model predicting maximum bat speed. Research in other sports has shown that higher skilled baseball players exhibit a longer stride phase (Welch et al., 1995; Escamilla et al., 2009) and that higher skilled golfers exhibit a greater and faster weight shift between feet. Such lower body technique aspects may still play a role in successful range hitting in cricket, but are of lesser importance than the upper body parameters included in the regression model.

The three kinematic parameters that best explain the variation in maximum bat speed during the downswing occur in a proximal to distal order of importance, with the proximal motion being a stronger predictor in the regression model. The order of importance would suggest that rotation of the more proximal pelvis and upper thorax segments, generating a large transverse separation, is critical to generating high bat speeds, as acceleration of the distal segments is likely to be less effective without energy transfer from these segments. A greater magnitude of rotation or extension allows the batsman a greater range through which to accelerate each segment, in turn leading to an increased segmental velocity and maximum bat speed during the downswing. For the trials used in the kinematic analysis, the mean intra-participant standard deviation for carry distance and ball launch speed varied little between participants of different playing abilities and did not vary in any systematic way. It can therefore be assumed that the effects of averaging the kinematics of the best three trials per participant were similar for each participant and were not a function of playing ability.

In addition to the clear application of the identified important kinematic technique factors to batting coaching, the findings of this study could also be applied to the development of physical training programmes for cricket batsmen, particularly those specialising in one-day cricket where range hitting is a priority. The results provide biomechanical support for training programmes like that developed by Lephart et al. (2007). This programme achieved non-significant increases in the important X-factor measure during the golf swing through exercises targeting an increase torso rotational flexibility. Future research should investigate whether similar training can improve cricket range hitting in a causal way through an increase in X-factor at the commencement of the downswing.

The primary limitation to the present study is the small sample size compared to existing regression studies (Folland et al., 2017). Although this limits the power of any statistical tests, there is a sufficient sample to identify those variables best explaining the observed variation in each dependent variable, particularly when considering the primarily elite batsmen studied here. Secondly, although the use of each batsman's own bat ensured realistic kinematics, differences in material properties, length, shape, and inertial properties may have affected ball launch speed, and could account for some of the unexplained variation within the data. Previous work has shown little difference in batted ball speed for a given impact location, or impact location-ball speed relationship between different bats (Symes, 2006; Peploe et al., 2018) and indeed the benefits of participants using their own bats likely outweigh any negligible negative effects. It should also be noted that bat mass was not significantly correlated with ball launch speed ($r = 0.051$, $P = 0.446$) and as such not included in the regression models. Although the spin imparted on the ball during impact could influence carry distance (Sawicki et al., 2003), this was not measured in the current study or readily available within existing literature, and as such was not considered. Finally, the heterogenous ability range of the present study's sample population should be carefully considered when applying the findings to any specific individual or group of athletes.

In conclusion, the parameters that best explain the variation in carry distance, ball launch speed, vertical ball launch angle, and bat speed during a range hitting task in cricket have been identified. Trials with an impact location near the sweetspot and a high bat speed at impact were found to generate high ball launch speeds, while a bat angle further forward beyond vertically downwards about the global medio-lateral axis resulted in higher vertical launch angles. Batsmen exhibiting an increased separation between the pelvis and upper thorax in the transverse plane (X-factor) at the commencement of the downswing, as well as increased lead elbow extension and wrist uncocking during the downswing, were found to generate higher maximum bat speeds in the approach to impact. Players and coaches should focus on generating central impacts with the highest possible bat speed, utilising the kinematic recommendations to improve technique and develop suitable training programmes to enhance performance. Future studies should investigate the kinetic chain in more detail, and the extent to which this is utilised in range hitting, as well as identifying any kinematic differences between skilled male and female batters that may inform more specific training regimes for each group.

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REFERENCES

Baker, R. (2001). Pelvic angles: a mathematically rigorous definition which is consistent with a conventional clinical understanding of the terms. Gait & Posture, 13(1), 1–6.

Bell, A. L., Brand, R. A., & Pedersen, D. R. (1989). Prediction of hip joint centre location from external landmarks. Human Movement Science, 8(1), 3–16.

Bower, R. (2012). The sweet spot of a cricket bat for low speed impacts. Sports Engineering, 15(2), 53–60.

Bowerman, B. L., & O'Connell, R. T. (1990). Linear statistical models: An applied approach (2nd ed.). Belmont, CA: Duxbury.

Cheetham, P. J., Martin, P. E., Mottram, R. E., & St Laurent, B. F. (2001). The importance of stretching the "X-Factor" in the downswing of golf: The "X-Factor Stretch." Optimising Performance in Golf, 1, 192–199.

Chu, Y., Sell, T. C., & Lephart, S. M. (2010). The relationship between biomechanical variables and driving performance during the golf swing. Journal of Sports Sciences, 28(11), 1251–1259.

Cork, A., Justham, L., & West, A. A. (2010). Batter's behaviour during training when facing a bowling machine and when facing a bowler. Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology, 224(3), 201–208.

Draper, N. R., & Smith, H. (1998). Applied regression analysis (3rd ed.). New York, NY: Wiley.

Elliott, B. C., Blanksby, B. A., & Ellis, R. (1980). Vibration and rebound velocity characteristics of conventional and oversized tennis rackets. Research Quarterly for Exercise and Sport, 51(4), 608–615.

Elliott, B., Baker, J., & Foster, D. (1993). The kinematics and kinetics of the off-drive and on-drive in cricket. Australian Journal of Science and Medicine in Sport, 25(2), 48–54.

Escamilla, R. F., Fleisig, G. S., DeRenne, C., Taylor, M. K., Moorman, C. T., Imamura, R., … Andrews, J. R. (2009). A comparison of age level on baseball hitting kinematics. Journal of Applied Biomechanics, 25(3), 210–218.

Ettema, G. J. C. (2001). Muscle efficiency: The controversial role of elasticity and mechanical energy conversion in stretch-shortening cycles. European Journal of Applied Physiology, 85(5), 457–465.

Field, A. P. (2013). Discovering statistics using IBM SPSS Statistics (4th ed.). London: Sage.

Fleisig, G. S., Hsu, W. K., Fortenbaugh, D., Cordover, A., & Press, J. M. (2013). Trunk axial rotation in baseball pitching and batting. Sports Biomechanics, 12(4), 324–333.

Folland, J. P., Allen, S. J., Black, M. I., Handsaker, J. C., & Forrester, S. E. (2017). Running Technique is an Important Component of Running Economy and Performance. Medicine and Science in Sports and Exercise, 49(7), 1412–1423.

G. Tabachnick, B., & S. Fidell, L. (2007). Using Multivariate Statistics. Pearson Education, Inc. (Vol. 28).

Gibson, A. P., & Adams, R. D. (1989). Batting stroke timing with a bowler and a bowling machine: A case study. Australian Journal of Science and Medicine in Sport, 21(2), 3–6.

Gordon, B. S., Moir, G. L., Davis, S. E., Witmer, C. A., & Cummings, D. M. (2009). An investigation into the relationship of flexibility, power, and strength to club head speed in male golfers. Journal of Strength and Conditioning Research, 23(5), 1606–1610.

Hanavan, E. P. (1964). A mathematical model of the human body. Aerospace, 1–149.

Hume, P. A., Keogh, J., & Reid, D. (2005). The role of biomechanics in maximising distance and accuracy of golf shots. Sports Medicine, 35(5), 429–449.

Koenig, G., Tamres, M., & Mann, R. W. (1994). The biomechanics of the shoe-ground interaction in golf. In Science and Golf II. Proceedings of the World Scientific Congress of Golf, 40–45.

Komi, P. V. (2000). Stretch-shortening cycle: A powerful model to study normal and fatigued muscle. Journal of Biomechanics, Vol. 33, 1197–1206.

Komi, P. V. (1984). Physiological and biomechanical correlates of muscle function: effects of muscle structure and stretch-shortening cycle on force and speed. Exercise and Sport Sciences Reviews.

Landlinger, J., Lindinger, S. J., Stöggl, T., Wagner, H., & Müller, E. (2010). Kinematic differences of elite and high-performance tennis players in the cross court and down the line forehand. Sports Biomechanics, 9(4), 280–295.

Lephart, S. M., Smoliga, J. M., Myers, J. B., Sell, T. C., & Tsai, Y. S. (2007). An eight-week golf-specific exercise program improves physical characteristics, swing mechanics, and golf performance in recreational golfers. Journal of Strength and Conditioning Research, 21(3), 860–869.

Linthorne, N. P. (2001). Optimum release angle in the shot put. Journal of Sports Sciences, 19(5), 359–372.

Linthorne, N. P., & Everett, D. J. (2006). Release angle for attaining maximum distance in the soccer throw-in. Sports Biomechanics, 5(2), 243–260.

McLean, J. (1992). Widen the gap. Golf Magazine, 49–53.

Menard, S. (1995). Applied logistic regression analysis: Sage University series on quantitative applications in the social sciences. Thousand Oaks, CA: Sage.

Myers, J., Lephart, S., Tsai, Y., Sell, T., Smoliga, J., & Jolly, J. (2008). The role of upper torso and pelvis rotation in driving performance during the golf swing. Journal of Sports Sciences, 26(2), 181–188.

Myers, R. (1990). Classical and modern regression with applications (2nd ed.). Boston, MA: Duxbury.

Narayanan, A. (2013). ODI boundary stats over the years. [Blog] View from third slip. Available at: http://www.espncricinfo.com/blogs/content/story/686539.html [Accessed 30 July 2018].

Peploe, C. (2016). The kinematics of batting against fast bowling in cricket. PhD Thesis, Loughborough University.

Peploe, C., King, M., & Harland, A. (2014). The effects of different delivery methods on the movement kinematics of elite cricket batsmen in repeated front foot drives. In Procedia Engineering, Vol. 72, pp. 220–225.

Peploe, C., McErlain-Naylor, S. A., Harland, A. R., Yeadon, M. R., & King, M. A. (2017). A curve fitting methodology to determine impact location, timing, and instantaneous post-impact ball velocity in cricket batting. Proceedings of the Institution of Mechanical Engineers Part P-Journal of Sports Engineering and Technology.

Peploe, C., McErlain-Naylor, S., Harland, A., & King, M. A. (2018). The relationships between impact location and post-impact ball speed, bat torsion, and ball direction in cricket batting. Journal of Sports Sciences, 36(12), 1407–1414.

Petersen, C., Pyne, D. B., Portus, M. J., & Dawson, B. (2008). Analysis of Twenty/20 cricket performance during the 2008 Indian Premier League. International Journal of Performance Analysis in Sport, 8(3), 63–69.

Pinder, R. A., Davids, K., Renshaw, I., & Araújo, D. (2011). Manipulating informational constraints shapes movement reorganization in interceptive actions. Attention, Perception, & Psychophysics, 73(4), 1242–1254.

Renshaw, I., Oldham, A. R., Davids, K., & Golds, T. (2007). Changing ecological constraints of practice alters coordination of dynamic interceptive actions. European Journal of Sport Science, 7(3), 157–167.

Robinson, R. L. (1994). A study of the correlation between swing characteristics and club head velocity. In Science and golf II: Proceedings of the 1994 World Scientific Congress of Golf, 84–90.

Sawicki, G. S., Hubbard, M., & Stronge, W. J. (2003). How to hit home runs: Optimum baseball bat swing parameters for maximum range trajectories. American Journal of Physics, 71(11).

Seeley, M. K., Funk, M. D., Denning, W. M., Hager, R. L., & Hopkins, J. T. (2011). Tennis forehand kinematics change as post-impact ball speed is altered. Sports Biomechanics, 10(4), 415–426.

Sprigings, E. J., & Neal, R. J. (2000). An insight into the importance of wrist torque in driving the golfball: A simulation study. Journal of Applied Biomechanics, 16(4), 356–366.

Stretch, R., Buys, F., Toit, E. Du, & Viljoen, G. (1998). Kinematics and kinetics of the drive off the front foot in cricket batting. Journal of Sports Sciences, 16(8), 711–720.

Stuelcken, M. C., Portus, M. R., & Mason, B. R. (2005). Off-side front foot drives in men's high performance cricket. Sports Biomechanics, 4(1), 17–35.

Symes, A. W. (2006). The effect of mass distribution on cricket bat playing properties. Loughborough University.

Taliep, M., Galal, U., & Vaughan, C. (2007). The position of the head and centre of mass during the front foot off-drive in skilled and less-skilled cricket batsmen. Sports Biomechanics, 6(3), 345–360.

Tsunoda, M., Bours, R., & Hasegawa, H. (2004). Three-dimensional motion analysis and inverse dynamic modelling of the human golf swing. SAE Transactions, 113(7), 267–275.

Wallace, E. S., Graham, D., & Bleakley, E. W. (1990). Foot-to-ground pressure patterns during the golf drive: a case study involving a low handicap player and a high handicap player. In Science and golf: Proceedings of the First World Scientific Congress of Golf 25–29.

Watts, R., & Baroni, S. (1989). Baseball-bat collisions and the resulting trajectories of spinning balls. American Journal of Physics, 57(1), 40–5.

Welch, C. M., Banks, S. A., Cook, F. F., & Draovitch, P. (1995). Hitting a baseball: A biomechanical description. Journal of Orthopaedic & Sports Physical Therapy, 22(5), 193–201.

Wherry, R. J. (1931). A new formula for predicting the shrinkage of the coefficient of multiple correlation. The Annals of Mathematical Statistics, 2(4), 440–457.

Winter, D. A. (2009). Biomechanics and motor control of human movement (4th ed.). Canada: Wiley-Interscience.

Worthington, P. J., King, M. A., & Ranson, C. A. (2013). Relationships between fast bowling technique and ball release speed in cricket. Journal of Applied Biomechanics, 29(1), 78–84.

Zhang, Z., Li, S., Wan, B., Visentin, P., Jiang, Q., Dyck, M., … Shan, G. (2016). The influence of X-factor (trunk rotation) and experience on the quality of the badminton forehand smash. Journal of Human Kinetics, 53(1), 9–22.

Zheng, N., Barrentine, S. W., Fleisig, C. S., & Andrews, J. R. (2008). Kinematic analysis of swing in pro and amateur golfers. International Journal of Sports Medicine, 29(6), 487–493.