THE KINEMATICS OF BATTING AGAINST FAST BOWLING IN CRICKET

by

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ABSTRACT

In cricket, batting against a fast bowler is thought to be one of the most challenging tasks a player must undertake. Despite this, minimal research exists investigating the techniques used by batsmen, with the majority of research focussed on injury mechanisms and pace generation in fast bowlers. The aim of this study was to investigate the techniques used by elite and amateur batsmen in a training environment, such that key aspects of batting technique relating to success could be extracted, and recommendations for future coaching practice and player development could be made. A novel methodology was developed for the collection of full body three-dimensional kinematic data of cricket batsmen in a realistic training environment. Kinematic and high-speed video (250 Hz) data were collected for 31 batsmen, and a three-dimensional full body biomechanical model was developed. Batsmen performed forward drive and pull shots against different delivery methods. Key events and kinematic parameters were defined, and used to produce detailed biomechanical descriptions of the forward drive and pull shots. A curve fitting methodology was developed and validated to determine the impact location of the ball on the bat face, and used to investigate the effects of impact location on shot outcome during a range hitting task. Impacts further from the sweetspot were found to generate lower ball speeds and decrease shot accuracy through bat twist. Investigations into the presence of movement variability during the forward drive and pull shots, the differences in batsman response when facing different delivery methods, and the aspects of batting technique characterising the longest hitters in a range hitting task were also carried out. Studies identified the commencement of the downswing as a critical event due to the decreased timing and kinematic variability, with larger variation in kinematic parameters occurring during the downswing. Batsmen exhibited fundamentally different techniques against the bowling machine compared to the bowler due to their pre-release knowledge of ball bounce location, while responses against the Sidearm ball thrower were more similar despite the lower ball speed. Finally, batsmen generating the largest carry distances in a range hitting task were found to generate a large separation of the pelvis and thorax in the transverse plane (Z-factor) during the downswing, as well as greater front elbow extension and wrist uncocking. The methodology developed in this study provides a basis for continued investigation into the kinematics of cricket batting in a realistic training environment, allowing researchers to assess and make recommendations to improve current and future batting technique and coaching methods.

PUBLICATIONS

Published Papers:

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

Conference Presentations:

Peploe, C., McErlain-Naylor, S.A., and King, M.A. (2015). Determining impact location in cricket: a curve fitting methodology. MathSport International Conference, Loughborough University, 29 June – 1 July.

Peploe, C., King, M.A., and Harland, A.R. (2015). The effects of different ball delivery methods on the kinematic response of elite cricket batsmen in repeated pull shots. *Proceedings of the 5th World Congress of Science and Medicine in Cricket*, 23-27 March 2015, pp. 86.

Peploe, C. and Harland, A.R. (2014). A method for capturing three-dimensional kinematics of a cricket batsman in a training environment. 1st International Conference in Sports Science and Technology, Nanyang Technological University, Singapore, 11-12 September

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CHAPTER 1

INTRODUCTION

1.1 Chapter Outline

This chapter provides details of the reasoning and motivation for this research, as well as an outline of previous research carried out in this area. The purpose of the research is explained, and a number of research aims and questions are posed. Finally, an overview of each chapter of this thesis is provided with a brief description of its content.

1.2 The Area of Study

Simply put, cricket is a game of batsman against bowler, where the batsman attempts to hit the ball, evade the fielders, and score runs. Batsmen have a range of batting shots they can call upon to impact the ball, which can be delivered at speeds around 40 ms^{-1}, and can deviate laterally and vertically in the air or off the pitch surface. Anecdotally, batting against an elite fast bowler is one of the most challenging tasks a batsman must undertake, with the bowler attempting to use the speed of their delivery to reduce the available time a batsman has to view and intercept the ball.

Interestingly, limited research has focussed on the skill of batting in cricket, with the majority of studies instead choosing to investigate fast bowling, with a particular emphasis on lower back motion and injury (e.g. Ranson et al., 2008) and pace generation (e.g. Worthington et al., 2013). Existing batting research has focussed primarily on the relationship between skill level and anticipation (Abernethy & Russell, 1984; Penrose & Roach, 1995), the sources of pre-release cues (Müller et al., 2006; Müller et al., 2009) and the effects of their alteration or removal through use of a bowling machine (Gibson & Adams, 1989; Renshaw et al., 2007; Pinder et al., 2009, 2011a; Cork et al., 2010), and visual strategy (Land & McLeod, 2000; Croft & Button, 2009; Mann et al., 2013). While some research has gone into more depth concerning the kinematics of batting (Elliott et al., 1993; Stretch et al., 1998; Stuelcken et al., 2005; Taliep et al., 2007), these have often been descriptive studies of the forward drive technique performed by a small sample of batsmen, with various playing abilities, hitting forward drives in an unrealistic performance environment, usually with no consideration of the specificity to accurate task constraints required to gain an accurate and realistic response, or the resulting success of the shot. There is also currently no consensus in the research literature on the techniques used by elite batsmen when executing the forward drive or any other batting shot, forcing players and coaches to rely solely upon the experiences and knowledge of past players and coaches.

A three-dimensional analysis of batting kinematics has the potential to provide a more thorough and in-depth understanding of batting against fast bowling in cricket. This will allow current coaching strategies to be better informed and potentially reassessed, as well as giving developing and elite players and coaches a greater grasp on the techniques used in different batting shots.

1.3 Statement of Purpose

A methodology for full body three-dimensional kinematic analysis of cricket batting techniques in a realistic training environment will be developed and used to capture kinematic data on a group of elite and amateur batsmen. A biomechanical model will be defined along with a series of key events throughout the batting shots investigated, enabling detailed analysis of batting technique and assessment of batsman response under specific practice conditions. This will be accompanied by a methodology for determining the impact location of the ball on the bat face, and its resulting effect on shot outcome.

Outputs from the biomechanical model will first be used to provide a thorough biomechanical description of the techniques used by the batsmen in the two main shots investigated in this study; the forward drive and the pull shot. Further analyses will look to investigate the presence of movement variability in the two batting shots, identify differences in batsman response when facing different delivery methods, and examine the relationships between aspects of batting technique and ball carry distance in a range hitting task. Throughout this research, recommendations will be made for application of findings to player development and coaching practice, in the hope that key aspects of batting technique related to success can be extracted and applied by those in the elite game.

1.4 Research Questions

Q1. What are the techniques and movement timings employed by batsmen in the forward drive and pull shots?

Technical recommendations in batting are currently primarily based on the opinions and methods used by previous players, with minimal research being conducted into the actual kinematics exhibited during different shots by elite batsmen. The analysis performed will provide detailed assessments of the techniques used by the batsmen in this study during both the forward drive and pull shots, and answer a series of questions revealed within the data. This will provide a depth of data for future research, begin to highlight areas of batting technique warranting further study, and potentially identify important factors and relationships for consideration in coaching and player development.

Q2. What are the effects of ball on bat impact location on batting shot outcome?

The impact location of the ball on the bat face has always been perceived as an important measure of success in cricket batting, with impacts near the sweetspot (a point on the blade where impact causes minimal vibrations through the handle) of the bat being thought to result in higher ball speeds, less bat twist, and more accurate placement of the ball towards the target. Although this is commonly assumed knowledge across the cricketing world, no research has yet investigated in detail or attempted to quantify the relationships. The analysis performed will allow the relationships between impact location and resulting ball speed, bat twist, and ball direction to be identified and quantified, resulting in a more thorough understanding of the margin for error a batsman faces when impacting the ball.

Q3. How much movement variability is present during repeated shots in cricket batting, and how does it vary according to skill level and delivery method?

Previous research into expertise and movement variability during repeated movements has found trends in both directions; that is experts have been shown to exhibit both higher and lower variability than lesser skilled athletes, and no research has been carried out in cricket. The analysis performed will provide an initial insight into the movement variability present in cricket batting, for both elite and amateur batsmen hitting a static ball off a batting tee and against a bowling machine, focussing particularly on shot outcome, movement timings, and wrist, elbow, and bat kinematics.

Q4. What are the effects of facing different delivery methods on batsman response?

While some research has been carried out examining the effects of facing a bowling machine compared to a bowler (Gibson & Adams, 1989; Renshaw et al., 2007; Pinder et al., 2009, 2011a; Cork et al., 2010), these studies have yet to form a consensus on the specific kinematic or movement timing differences present, and have not incorporated the use of the Sidearm ball thrower into their investigations. Moreover, existing studies have been carried out using two-dimensional video footage, considered only front foot shots, and using single subject or small samples of players with a range of abilities, making generalisation of results to the rest of the population difficult. The analysis performed will provide a more in-depth understanding of the movement timing and kinematic differences exhibited by batsmen when facing the different delivery methods, allowing a discussion and review of current coaching practices to be undertaken.

Q5. Which aspects of batting technique characterise the longest hitters in a range hitting task?

The ability of a batsman to hit the ball over large distances is a vital skill in the modern game. Although the technical features important to generating bat/clubhead speed in other hitting sports such as golf and baseball are well understood, no such research has investigated range hitting in cricket. The analysis performed will enable those aspects of technique which best characterise the longest hitters to be identified, and the mechanics by which batsmen generate bat and ball speed to be more thoroughly understood.

1.5 Chapter Organisation

Chapter 2 provides a thorough review of the research conducted into and surrounding the topic of batting against fast bowling in cricket. The temporal and spatial demands of batting against fast bowling are reviewed, along with a discussion of the methods elite batsmen use to overcome these demands, such as anticipation, visual strategy, and perception to action theories. Previous kinematic and kinetic studies in cricket batting are also reviewed, as well as research from other hitting sports examining the generation of bat/clubhead speed and expertise. Finally, a multidisciplinary approach to batting research is outlined and recommended as the way forward for future studies.

Chapter 3 describes the protocols and equipment used to collect the kinematic data required, including the design and development of novel marker sets, and the experimental setup. The subjects participating in the research are also presented, as well as an outline of the data collection procedure that was carried out.

Chapter 4 provides details of the data processing steps undertaken in order to later analyse and draw conclusions from the kinematic data. The calibration of the three-dimensional motion capture system is discussed, as well as the methods used to reconstruct, label, filter, and interpolate the data. The biomechanical model used throughout the research is presented, as well as descriptions of the key events and kinematic variables used for later analysis.

Chapter 5 provides a thorough biomechanical description of the techniques used by the subjects participating in this study when playing a forward drive and pull shot. A number of reported/proposed relationships between batting technique aspects are also investigated using simple statistical analyses.

Chapter 6 outlines and validates the methodology used for the determination of the impact location of the cricket ball on the bat face. It also investigates the effect of impact location on resulting shot success in terms of post-impact ball speed and direction, as well as post-impact bat twist.

Chapters 7 – 9 address the three primary research questions posed in section 1.4. Chapter 7 investigates the variability present in batting shots when hitting a static ball and against a bowling machine, for both elite and amateur batsmen, offering comparisons between the two groups and conditions present. Chapter 8 explores the effects of facing different delivery methods on batsman response in the forward drive and pull shots, and discussed the implications of any differences. Chapter 9 uses linear regression to address relationships between carry distance, ball speed, and bat speed in a range hitting task, attempting to identify the critical factors in generating large carry distances when hitting over the top.

Chapter 10 summarises the contents of this thesis and identifies the perceived limitations present throughout. The research questions posed at the start of this thesis are addressed, and potential future studies as a result of this work are proposed.

CHAPTER 2

LITERATURE REVIEW

2.1 Chapter Outline

The ability of an elite batsman to forcefully intercept a fast moving ball with sufficient temporal and spatial accuracy to create a successful impact outcome is a highly complex and refined skill. To ensure that the bat arrives at the intended impact location with the desired velocity and orientation at the same time as the ball requires intricate coordination of the visual and neuromuscular systems, demanding accurate prediction of the ball's trajectory while simultaneously coordinating a series of movements involving several muscle groups.

This chapter initially seeks to quantify the temporal and spatial constraints imposed on a batsman by a fast bowler, and then outlines some of the methods batsmen use in order to overcome these constraints. Anticipation and visual strategy are discussed, followed by the presentation of two contrasting theories concerning the link between perception and action in successful hitting. The notion of the visual-motor delay is then introduced, and consequently a hybrid control mechanism for cricket batting, consisting of aspects of each theory previously discussed, is proposed. The concept of movement variability is also examined in relation to the perception-to-action theories previously discussed, and a collaborative theory of movement variability is presented.

Having discussed the visual-motor control of hitting, the kinematics and kinetics of cricket batting and similar hitting motions are then discussed. Firstly, previous studies into batting kinematics and kinetics are reviewed and critiqued, and comparisons drawn between the findings and existing coaching recommendations. This is followed by an overview of kinematic and kinetic studies into other hitting sports such as baseball and golf, with a particular focus on bat/clubhead speed generation. Limitations and gaps in the research are highlighted throughout, and finally recommendations are made for more multidisciplinary approaches to batting research to be employed in future studies.

2.2 The Temporal and Spatial Constraints of Batting

When batting against an elite fast bowler who releases the ball at speeds of 32 – 40 ms^{-1} (Worthington et al., 2013), a batsman has approximately 500 ms from the moment of ball release to judge the future arrival point of the ball, and move into an appropriate position with body and bat to successfully intercept it (Abernethy, 1981). In fact, for a successful impact to be achieved the batsman is required to intercept the ball within a temporal window of 2-5 ms, and with a spatial accuracy of less than 5 cm (Regan, 1992), also considering they very rarely have an in-line view of the approaching ball (Figure 2.1). Figure 2.1 shows the physical parameters (v = velocity, t = time to/from bounce, y = ball height at impact, L = horizontal distance from release to impact), and visual measurements (θ = viewing angle to ball release, ϕ = viewing angle to ball bounce) available to a batsman to make judgements on ball arrival time and location. The batsman may also have to contend with changes in ball direction in the air (swing) or off the pitch (seam movement or spin), speed, and trajectory, each produced by the bowler with the aim of causing misjudgements in ball arrival time and position. The sheer complexity of this interceptive task is further increased due to the need to control bat velocity and spatial orientation in order to avoid opposition fielders and actually score runs. These severe constraints place expert performance at the very limits of human skill, creating problems for the batsman in terms of reaction and movement times, decision making, and spatial accuracy (Müller & Abernethy, 2012).

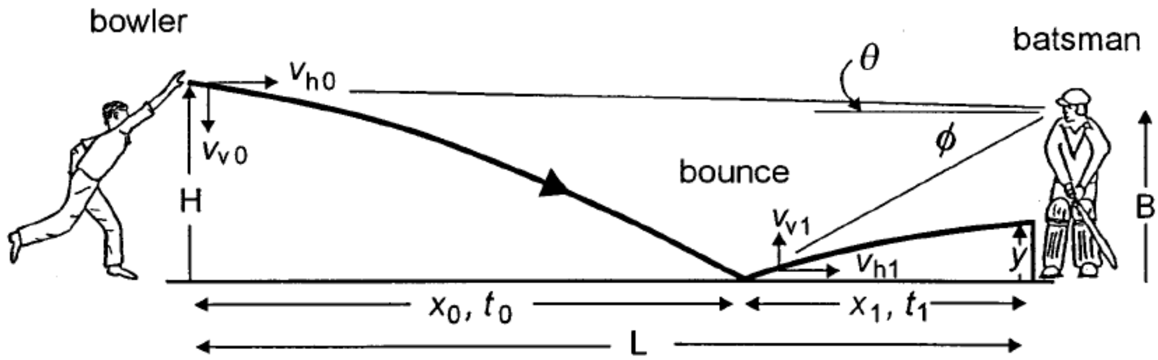


Figure 2.1: The physical parameters that determine where and when the ball will reach the batsman, and the measurements he can make to determine the time and point of contact (adapted from Land & McLeod, 2000).

2.3 Overcoming the Temporal Constraints of Batting

As described previously, the temporal constraints of batting against a fast bowler in cricket are immense. Traditional human reaction and movement time studies (Abernethy, 1981; McLeod, 1987) suggest that the 500 ms total time given by an elite fast bowler to intercept the ball is significantly less than the sum of the visual reaction time and the movement time that the human is capable of producing, which are typically around 200 ms and 700 ms respectively (Abernethy, 1981). Gibson & Adams (1989) proposed that combined choice reaction and movement times for a decision from four possible shots totals approximately 700 ms, with 900 ms being the time required for a nine shot decision. Plainly this limitation is something elite batsmen overcome, utilising a number of methods that allow them to intercept the ball with sufficient accuracy and timing for a successful shot.

2.3.1 Anticipation

One of the key strategies used by elite sportspeople to overcome high temporal constraints is anticipation (Sarpeshkar & Mann, 2011). By identifying and interpreting advanced information from the movements and kinematics of the opponent (Figure 2.2), athletes can perceive pre-flight information regarding the future trajectory of the ball, allowing them to begin to organise movements before the ball is released, thus giving them longer to view and interpret ball flight information in order to fine tune the bat swing (Abernethy, 1981; Müller & Abernethy, 2012).

Figure 2.2: An example of the fast bowling action from which a batsman gains vital visual cues.

2.3.1.1 The Relationship between Expertise and Anticipatory Skill

The presence of superior anticipatory skill amongst expert sportspeople has been investigated across a range of sporting activities, finding that advanced cue information is vital to successful interception in fast ball sports. In baseball, Ranganathan & Carlton (2007) showed that expert hitters are better able to use differences in the pitcher’s kinematics to determine ball trajectory and delivery type, also showing that the initiation of the forward stride was coupled not to the ball flight but to the pitcher's movements. Similar conclusions were drawn in tennis (Shim et al., 2005; Tenenbaum et al., 1996; Goulet et al., 1989), badminton (Abernethy & Russell, 1987), squash (Abernethy, 1990), and volleyball (Wright et al., 1990), where skilled and experienced players were more accurate than novices in predicting shot type and direction as a result of their opponent's kinematics. While an increased skill level often comes with age, hours of experience seem to have more of an effect on anticipatory ability than age alone (Abernethy, 1988; Weissensteiner et al., 2008).

Expert baseball hitters were also shown to be superior to less-skilled hitters in using situational probability information to predict the upcoming pitch type (Paull & Glencross, 1997; Gray, 2002). This is the ability of a player to predict the next delivery type based on the previous set of deliveries, the situation of the game, and the field positioning. Skilled squash players were also found to utilise situational probability to predict shot location when little or no kinematic cues were available (Abernethy et al., 2001). A similar system is suggested by Körding and Wolpert (2004) in tennis, who advocate a Bayesian strategy combining information from visual cues and prior knowledge of likely ball bounce locations to produce accurate estimations. Clearly this ability develops through practice and experience, and may help initiate faster responses once confirmatory information becomes apparent through the opponent's kinematics or ball flight information.

Previous studies on cricket batting have identified a clear relationship between skill level and anticipation, suggesting that expert players gain more information about delivery type and direction from pre-release cues than lesser-skilled players. Penrose & Roach (1995) showed that expert batsmen are more able to utilise advance cues to predict ball bounce length, while Abernethy & Russell (1984) found that expert batsmen make earlier and more accurate movements than novices based on advance cues. Skilled players also displayed superior ability to identify the point of ball release from kinematic cues (Gibson & Adams, 1989), and exhibited better discrimination of delivery type and direction against left and right arm bowlers (McRobert & Tayler, 2005) and different leg spin delivery types (Renshaw & Fairweather, 2000) based on kinematic cues from the bowler.

Although batsmen are seen to be able to anticipate a bowler's intentions, and expert batsmen have been shown to be more skilled at this than novice players, there are still several limitations to previous research surrounding anticipatory performance. Many studies rely on point-light displays or video simulations (Figure 2.3) to produce a verbal or written prediction of ball bounce location or direction (Abernethy & Russell, 1984; Renshaw & Fairweather, 2000; Penrose & Roach, 1995). While the use of video-based visual cues has been reconciled as producing similar responses from performers in terms of prediction skill level and learning (Farrow & Abernethy, 2002; Pinder et al., 2011a), the use of point-light displays has proven unrealistic to match conditions, with no differences in anticipatory skill being found in this environment between skilled and non-skilled players (Shim et al., 2005). A study by Mann et al. (2010) examining the ability of skilled batsmen to predict ball direction against a bowler in three conditions (verbal response, shadowed movement and attempting to intercept the ball), showed that not even elite batsmen could predict ball direction at an above-chance level using a verbal response. An improvement in prediction skill was seen when batsmen were allowed to produce physical movements, with maximal performance being found when batsmen were physically trying to hit the ball. Similar results were found by Farrow & Abernethy (2003) amongst novice and expert tennis players. This highlights the implicit and subconscious nature of the motor skills involved in batting, showing that only when batsmen are allowed to perform their well-trained motor programmes can they display maximum anticipatory skill, and emphasises the importance of realistic task constraints and intent to intercept the ball in future anticipatory and kinematic studies.

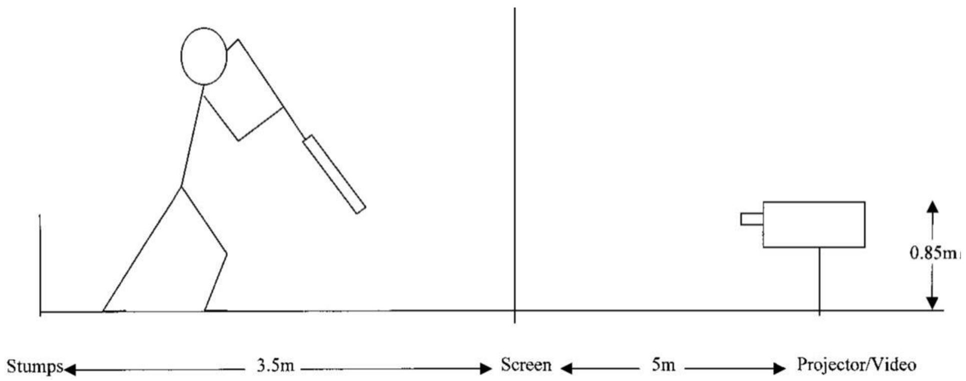


Figure 2.3: The video setup used by Renshaw & Fairweather (adapted from Renshaw & Fairweather, 2000).

2.3.1.2 The Sources and Timing of Visual Cues in Batting

Clearly, as well as the ability to anticipate a bowler's intentions, the sources and timing of advanced cues a batsman uses will affect their prediction accuracy. Investigations into the specific advanced cues used by expert and novice batsmen were carried out by Müller et al. (2006) through temporal and spatial occlusion methods (Figure 2.4). When batting against a bowler, expert players were found to rely not solely on the superior use of the same cues as novice players, but also to be attuned to additional earlier cues from the bowler's kinematics.

Whereas lesser-skilled players were found to extract most of their visual cues from the bowling hand, skilled batsmen adopted a more thorough search strategy, gathering additional kinematic cues from the bowler's head, shoulders, trunk, and bowling arm, particularly during the phase between the bowler's front foot contact and ball release. It is suggested that batsmen utilise pre-release visual cues from the bowler's kinematics to judge the length of the ball, then use later ball flight information to fine tune existing movements and guarantee a good contact (Müller et al., 2006; Müller et al., 2009). This theory is also supported by Golby (1989), who found that temporal occlusion of the middle section of ball flight caused significant errors in bat-ball contact quality. Similar findings are also present amongst expert badminton players, who are shown to anticipate the forcefulness of a shot based on lower body and kinetic chaining information, whereas cues later in the hitting action from the upper body and racket are used to anticipate shot direction (Abernethy & Russell, 1987; Abernethy, 1988; Abernethy et al., 2008).

In terms of the specific cues used, expert batsmen seem to be better at identifying the short ball based on pre-release cues than the full ball, perhaps due to the vastly different bowler kinematics, for example the increased trunk flexion between front foot contact and ball release (Müller et al., 2009). The findings suggest that early ball flight information is critical for judging full ball length and initiating movement, while advance cues are more reliable for anticipating the short ball. Experts were also found to use the angular relationship between the bowling arm and hand to help predict delivery type against swing and spin bowlers (Müller et al., 2006), in the same way players use the relationship between the hitting arm and racket in badminton to predict shot direction (Abernethy, 1988).

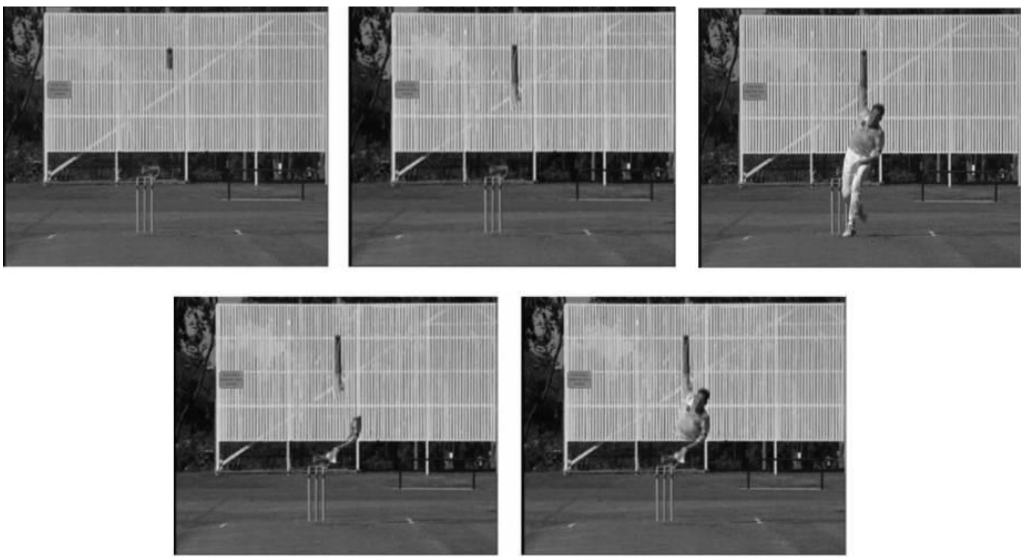


Figure 2.4: Spatial occlusion techniques used by Müller et al. (adapted from Müller et al., 2006).

2.3.1.3 The Effects of the Removal of Visual Cues on Batsman Response

Several studies have investigated the effect of removing or changing the advanced cues provided to a batsman, and the effect this has on their anticipatory ability. Skilled batsmen have been found to possess a tight coupling between the kinematics of the bowler and their own movements (Renshaw et al., 2007), and the removal of advance information has been found to negatively affect anticipatory skill and batting behaviour (Sarpeshkar & Mann, 2011). Such a removal of advanced information occurs when batting against a bowling machine; the batsman has no advanced cues from the kinematics of the bowler to help anticipate the forthcoming delivery (Müller et al., 2006). As such, several studies have found significant differences in the movement timing and kinematic response of batsmen when facing a bowling machine compared to when facing a bowler.

Gibson & Adams (1989) found large timing differences for a single elite subject when playing the front foot defensive, observing that the forward stride was completed earlier, and the downswing initiated later against a machine, probably due to some knowledge of ball bounce location prior to release. Cork et al. (2010) also found timing differences from a single non-elite subject between bowler and bowling machine conditions. The batsman in this case was found to initiate and complete their forward stride later against the machine, and respond more consistently in terms of movement timings against the bowler. The authors suggested that the batsman responded more consistently against the bowler due to a tight coupling to their opponent's kinematics (Figure 2.5), and that the larger temporal variation present against the bowling machine was due to the lack of advanced cues. While the results of these two studies seemingly contradict each other, the fact that both rely on single subject designs with players of vastly different skill levels provides a reasonable justification for the differences shown in results, and calls for further investigation with larger sample sizes.

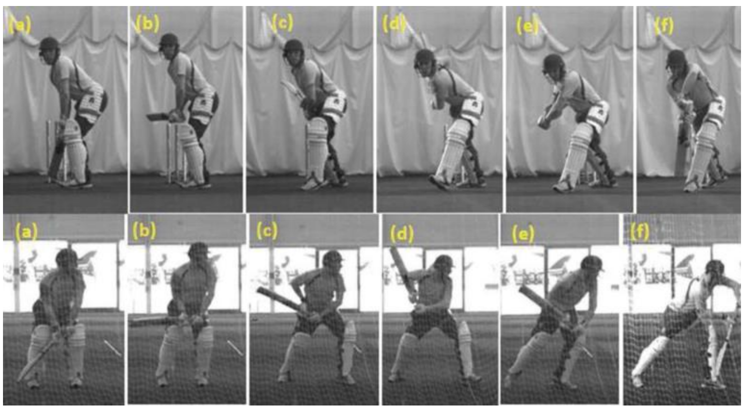


Figure 2.5: Still images of the batsman at key positions in the forward defensive shot to highlight their kinematics (adapted from Cork et al., 2010).

In a study of four high level club batsmen, Renshaw et al. (2007) found players to initiate their bat swing earlier against the bowling machine, as well as displaying a lower backswing, shorter forward stride, and slower bat speed in the downswing. This was attributed to players being more conservative against the machine in an attempt to prospectively control against late ball movement, although could equally be ascribed to players' knowledge of ball bounce location and speed prior to release. Batsmen were also found to have a strong coupling between the timing of the start of their backswing and the initiation of their forward stride when facing the bowler, perhaps indicating the presence of additional cues from which to time their actions.

More recently Pinder et al. (2009, 2011a) published two studies investigating the differences in timing and coordination of twelve developing cricketers when hitting forward defensive shots and drives against a bowling machine and a bowler. Batsmen were found to initiate their bat swing and forward stride later, as well as complete their stride later when facing the machine. Players also exhibited a shorter forward stride and lower backswing against the machine, as well as demonstrating lower bat speed in the downswing and lower quality bat-ball impacts. The authors suggest that experienced players develop and utilise a different set of visual cues when facing the bowling machine compared to the bowler to organise and time their movements. It is the job of the batsman, through training, to determine which of these cues are most useful in determining future ball arrival time and position, and to become better attuned to them. These are referred to as specifying (useful) and non-specifying (less useful) variables (Pinder, 2009). Due to the lack of bowler-specific advance cues, specifying variables from a bowling machine are based around the idiosyncrasies of the operator and information gained from the flight of the ball. While these variables are specifying against a bowling machine, they are likely to be non-specifying against a bowler, where cues from the bowler's kinematics are far more useful for early prediction of the delivery type, arrival time, and position. The authors hypothesise that the developing players in this study have not had sufficient exposure to the bowling machine to become accustomed to this different set of cues yet, so rely on later ball flight information and thus react and move later. Also, as with the study of Renshaw et al. (2007) above, a strong coupling was found between the timing of the start of the forward stride and the initiation of the backswing, however in this case in both the bowler and bowling machine conditions.

As a result of these studies, Pinder et al. (2011b) published a paper discussing the principles sports practitioners should apply when using ball projection machines in elite and developmental sport. The authors suggest that the key perception and action processes that guide performance should wherever possible remain coupled in a practice environment, highlighting the importance of realistic practice either using video simulation, middle practice, or additional variation programmed into a bowling machine. They propose that ball projection machines may be useful with developing players to establish more stable movement patterns, and with expert players to work on the areas of uncertainty and decision making against varying speeds/lengths, but warn coaches to be wary of using them for blocked practice of a single shot as this may inhibit the necessary flexibility and adaptability of technique, and cause an over-reliance on ultimately non-specifying variables.

Although the research presented above highlights a range of differences in batsman response and movement timings when batting against a bowling machine compared to a bowler, the results are often contradictory to each other, and there are a number of limitations across all the studies presented. Firstly, the standard and number of the players used varies substantially from study to study, from single subject designs (Gibson & Adams, 1989; Cork et al., 2010) to a sample size of twelve cricketers (Pinder et al., 2009; 2011a), and using developing, club, or elite players. This makes generalisation of the findings to the rest of the population difficult. Secondly, the ball speed is relatively low in all cases (27-33 ms^{-1} compared to speeds of up to $40ms^{-1}$ for elite fast bowlers; Worthington et al., 2013), and no consideration is given to back foot shots which make up a large proportion of the options available to a batsman (ECB, 2009). Lastly, all the studies presented have relied on digitised 2D video in order to gain kinematic data. This is likely to introduce errors in landmark identification, accurate event identification due to the relatively low frame rates used in digitising, and in the case of purely 2D methods neglects any movements in the sagittal plane or rotations about a vertical axis.

In a study designed to alter the visual cues provided to batsmen, Sarpeshkar et al. (2015) assessed the timing and coordination of 40 skilled and club batsmen playing front foot defensive shots in a number of different conditions against a ProBatter bowling machine (Figure 2.6). This device incorporates a life-size video image of a bowler into a bowling machine with accurate control of line, length, spin, and swing of the upcoming delivery. Two sets of trials were conducted, each containing a number of different conditions. In the first 18 trials the length of the delivery was randomised between full, good, and short lengths, but without swing on the ball. In the second set of trials the length was randomised again, but only between a good and a full length, while swing was also randomly manipulated via three conditions; no swing, outswing, and inswing. The authors then assessed the response of the batsmen when playing a forward defensive shot against good length deliveries only, using high-speed video footage (300 Hz). The video footage displayed to the batsmen was matched for each delivery such that the cues were accurate to the type of delivery bowled (length and swing direction), and all videos were of the same bowler. As well as differences between groups when facing the swinging ball (discussed in section 2.4.2), the authors found differences in the timing of movements for all batsmen when facing straight deliveries between the first and second set of trials. Batsmen were found to hit the ball earlier in the second set of trials without swing, thus impacting the ball further from the stumps. While the authors did not offer a direct explanation for this, it is likely that the knowledge of ball length (either good or full) allowed players to press forward and intercept the ball earlier in the second set of trials, as opposed to the first set where the threat of a short ball may have forced them to hang back and wait for additional cues. While this study is certainly a step in the right direction in terms of performing measurements in a realistic performance environment with large numbers of skilled batsmen, the fidelity of the ProBatter system is yet to be proven, thus the findings must be approached with some care. The authors did not record more detailed kinematics of each player, so it was not possible to understand in more depth the kinematic differences in response a batsman exhibits when facing the swinging ball.

Figure 2.6: The ProBatter cricket bowling machine (adapted from www.dailytelegraph.com.au).

Clearly, due to the wide range of limitations discussed previously, and the number of contradictions reported within the literature, further research is required in this area to clarify the differences in batsman response when facing different delivery methods, and make more informed recommendations to the cricket community. It is suggested that a larger scale study should be carried out in a realistic training environment, using elite players and ball speeds more similar to those seen in a performance situation. This high fidelity data capture environment is critical in ensuring a realistic response from the batsmen. Additional batting shots should also be examined, particularly those off the back foot, and other ball delivery methods used heavily in coaching, such as the Sidearm ball thrower, should be assessed in comparison to the bowling machine and bowler. Only having completed this more thorough analysis of batsman response to different ball delivery methods, can truly informed and valid recommendations be made regarding the application of each training device.

2.3.2 Visual Strategy

As well as anticipating delivery type and direction from bowler kinematics, a batsman must be able to estimate visually from its trajectory the future arrival time and location of an approaching ball (Regan, 1992). Elite batsmen have not been found to possess better reactions or 'supra-normal' vision compared to the general population (Mann, 2010), but are believed to have developed, through training, a better ability to effectively interpret visual information and modify their movements based upon their perceptions (McLeod, 1987).

The need to anticipate delivery type and direction from the bowler's action guides the initial strategy of the visual system; batsmen are found to focus on the bowler during his run up in a proximal to distal manner (Figure 2.7), in an attempt to interpret subtle kinematic variations that will aid in their prediction of the forthcoming delivery type and length (Croft & Button, 2009). Similar findings have been found amongst tennis and badminton players, who focus largely on their opponent in the initial phases of a service or shot (Abernethy & Russell, 1987; Goulet et al., 1989).

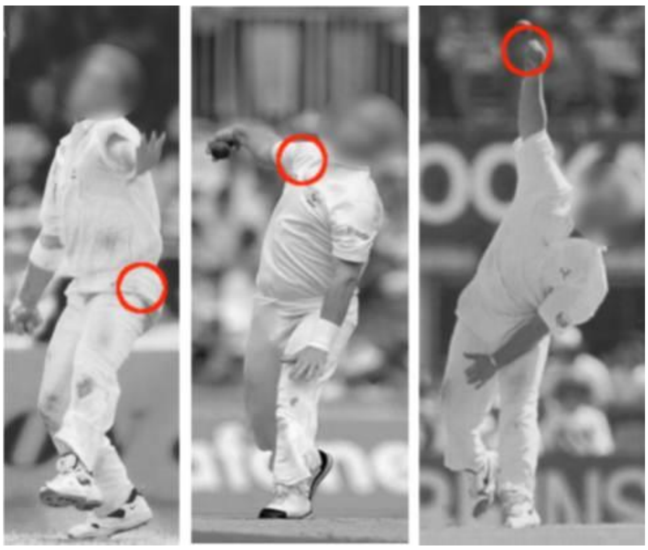


Figure 2.7: Examination of a batsman's gaze location on the bowler's approach (adapted from Croft & Button, 2009).

Differences again exist in visual strategy when facing a bowling machine. Due to the lack of kinematic cues from a bowler or opponent, batsmen are found to park their gaze at the release point of the bowling machine until the ball appears (Land & McLeod, 2000). Skilled players were found to react quicker to the emergence of the ball, and therefore produce a predictive saccade (where the eyes move ahead of the ball to a predicted future location) earlier than less-skilled players, perhaps suggesting they are attuned to cues from the machine operator and machine idiosyncrasies. As discussed in the previous section (2.3.1), this suggests that the overuse of the bowling machine for training will develop players with an over-reliance on ultimately non-specifying cues from ball flight and the machine operator, and not allow them sufficient practice in picking up and interpreting visual cues from a live bowler (Croft & Button, 2009).

When attempting to intercept a moving ball, humans have been shown to use a combination of pursuit tracking (slow rotations of the eyeballs to fixate the object in view) and predictive saccades to determine its arrival time and position (Croft et al., 2009). The studies of Land & McLeod (2000) and Croft et al. (2009) suggest that players initially pursuit track the ball immediately after release, before using a predictive saccade to reach the estimated bounce point ahead of the ball. They then wait for the ball to arrive at the bounce point, before attempting to track the rest of the flight before impact (Figure 2.8). However, players have been found to struggle to pursuit track the ball all the way to impact, with authors suggesting that the ball moves too quickly to track all the way to impact, thus a prediction must be made of the future ball arrival time and position based on existing information (Land & McLeod, 2000). This is supported by the finding that fuller and slower deliveries allow batsmen to pursuit track the ball for significantly longer periods of time, perhaps due to the lower stress on the visual system to keep up. While these studies produce some interesting results, they are limited by the fact they use a bowling machine as a ball delivery method, and the ball speeds are low (17 - 25 ms^{-1}) in comparison to an elite performance environment (32 - 40 ms^{-1}; Worthington et al., 2013), thus not stretching the visual system of the batsmen, and questioning the validity and applicability of the findings to a match situation.

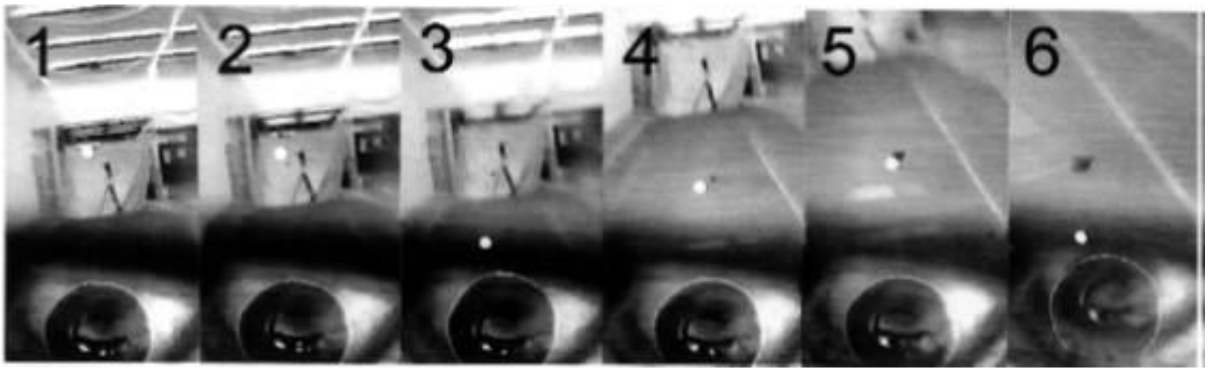


Figure 2.8: An example visual strategy of a batsman including pursuit tracking and a predictive saccade, showing the overall view and focus point of the eye throughout a delivery (adapted from Land & McLeod, 2000).

More recently, a study by Mann et al. (2013), investigated the visual strategy of two elite international cricket batsmen and two club batsmen when facing deliveries of three randomised lengths from a ProBatter ball projection machine. Interestingly the elite batsmen in this case were found to utilise a different visual strategy to the club players tested in this study and previously. These batsmen were found to keep their gaze ahead of the ball throughout its flight by coupling the rotation of their head to the motion of the ball, ensuring it stayed central in their field of vision when being tracked, as opposed to the club players who simply rotated their eyes, thus not keeping the ball centrally fixated. They also displayed either one or two very distinct predictive saccades based on the length of the delivery, which occurred earlier and were of a larger magnitude than those executed by the club players, who were in turn seen to be less consistent and later with their saccades. While two predictive saccades were used for good and short length deliveries, one to predict the bounce point and one to predict impact, only one saccade was used for full deliveries around the time of bounce, although the gaze remained ahead of the ball at all times. Remarkably, despite the eyes performing these predictive saccades ahead of the position of the ball, the strong coupling between the angle of the head and position of the ball remained throughout ball flight, so even after the saccade was complete the ball would be fixated centrally in the batsman's vision. This is thought to allow the batsman a better prediction of where in space the ball will arrive than if the ball were to move across the player's field of view.

As a result of these findings, the authors hypothesised that truly elite players possess the ability to direct the gaze towards the impact point, and thus watch the ball all the way to impact. They suggest that because of this, elite players may be able to use ball flight information within the final 200 ms of flight to perceive any late changes in trajectory and adjust their swing accordingly. They also propose that predictive saccades may not be produced purely because the ball is travelling too fast to track, but instead may have functional benefits. It is suggested that the use of a predictive saccade may assist in tracking the ball after bounce to neglect the relative increase in angular velocity of gaze required as the ball moves further down in the field of vision, in detecting and adapting to changes in trajectory after ball bounce, or in comparing the predicted and actual arrival point while trying to fine tune the bat swing. This theory is also supported by the work of Croft et al. (2009), who found no threshold speed below which no predictive saccade is used, suggesting that players prefer to employ a saccade even when the ball can be tracked throughout its flight.

While this basic visual strategy of pursuit tracking and predictive saccades is fairly well documented across a range of sports, the exact visual cues a cricket batsman uses are not fully understood. A number of authors have suggested that the information gained from early ball flight is unreliable and inadequate to precisely judge future ball arrival time and position (Regan, 1992; Gray, 2009; Croft & Button, 2009). Humans have been proven to possess poor sensitivity to the absolute distance and velocity of a ball, and are thus poor at early predictions of the future location of an accelerating ball. As such, the forward/back decision based on perceptions of ball length from early visual information is a difficult one, and therefore relies heavily on advanced cues and experience of previous deliveries (Gray, 2009).

Although early retinal information may be unreliable, as the ball approaches and viewing time increases, the quality of information that becomes available dramatically increases (Regan, 1992). It is in this middle and end stage of flight where human sensitivity to the time-to-contact variable, otherwise known as Tau, becomes critical. This variable was originally described by Lee (1976; 1980) with specific reference to use in driving a vehicle, and has more recently been applied in table tennis (Bootsma & van Wieringen, 1991), catching (Savelsbergh et al., 1991), hitting an accelerating ball (Lee et al., 1983), running over uneven ground (Warren et al., 1986), and adjusting strides in the long jump (Lee et al., 1982). In fact, temporal errors of 1.3-2.7% when estimating actual time-to-contact of an approaching object were found by Gray & Regan (1998); this approaches the accuracy required to fulfil the 2-5 ms temporal window set out by Regan (1992) to successfully intercept a fast moving ball. It is now widely accepted that this variable, regularly described as the rate of optical expansion of an approaching object on the retina, is the primary control variable for timing human interception (Gray, 2009). However, due to the presence of one or more predictive saccades in the visual strategy of all batsmen when intercepting a fast moving ball, constant estimation of time-to-contact is impossible. As such, players are thought to predict time-to-contact at various intervals surrounding their predictive saccades, and use existing kinematic cues from their opponent, prior ball flight information, and knowledge from previous deliveries to inform their decisions (Gray, 2009).

As well as the time-to-contact variable, humans are sensitive to a number of other visual cues that may influence their perception of ball arrival time and position. The vergence angle of the eyes (how rotated towards or away from each other they are in focussing) and angular size of the ball may be used within the final five metres of ball flight to assist in fine tuning the predicted time-to-contact measure (Gray, 2009). Batsmen are also thought to utilise binocular disparity (the difference between the location of an image in the left and right eye resulting from their horizontal separation) and stereomotion (the relative angular speeds of an image on the left and right retinas) to estimate ball passing point (Regan, 1992). Sensitivity to any changes in ball direction is highest when the ball is centrally fixated in a player's vision, and this effect is greatest when the ball is closer to the batsman and when the eyes are steady. While the use of these variables has not been proven in cricket, the fact that truly elite players attempt to couple the movement of their head to the movement of the ball, thus keeping the ball central in their field of view, suggests these as likely mechanisms for estimating the passing position of the ball.

2.4 Perception to Action Theories

The efficient perception and use of spatial and temporal information relating to the ball's future arrival position and time is vital to success in any hitting action. An expert performer must possess a refined link between the perceptual and motor systems to ensure that any information gained from the opponent's kinematics and ball flight is effectively used to position the body and time the swing of the bat (Sarpeshkar & Mann, 2011). This coupling between perception and action is stated to be a critical part of expertise in interceptive actions (Bootsma & van Wieringen, 1990; Ranganathan & Carlton, 2007), and as such guides skilful execution of batting in cricket.

Having investigated the perception of visual cues from the bowler and ball flight previously (section 0), this section explores the link between perception and action, and discusses how the human is capable of coordinating such complex interceptive actions as batting in cricket. Although a relatively large amount of research has been conducted in this area, there is still debate over how this feat is possible. Two primary schools of thought exist; predictive and prospective control.

2.4.1 *Predictive Control Theory*

Predictive control theory suggests that skilled performers possess a highly reproducible set of motor programmes (in this case batting shots) that have been learnt over time through training (Sarpeshkar & Mann, 2011). It argues that the limited information processing capabilities of the human, highlighted by studies finding human reaction times in the realms of 200 ms (McLeod, 1987) and indicating processing times of 700-900 ms for four and nine shot decisions respectively (Gibson & Adams, 1989), mean real-time creation of a unique movement is impossible within the given short time period, and that the performer must utilise significant previous knowledge of the action to achieve successful interception.

Tyldesley & Whiting (1975) proposed that through early perception of the situation and kinematics from the opponent and ball, performers will select the most appropriate response from their range of pre-learnt motor programmes. Once the movement has been selected, and can be executed in a known amount of time, the skill of the batsman lies in the ability to initiate it at the correct point to ensure the ball is hit at the intended moment of arrival. Any variation in movement time between trials is accounted for as a result of noise in the movement system or measurement error.

This theory requires the batsman to be able to predict with extreme accuracy, based on information from the bowler's kinematics and early ball flight, the exact arrival time and position of the ball. Although more recent iterations of this theory (Schmidt & Lee, 2005) allow for temporal scaling of each element of a movement to adjust for any changes in perception of the ball arrival time or location, the levels of prediction accuracy required from early ball flight information to successfully intercept the ball are thought to be unattainable (Sarpeshkar & Mann, 2011). This fact alone makes a purely predictive control mechanism for hitting unlikely.

2.4.2 *Prospective Control Theory*

Prospective control theory suggests that rather than having a pre-programmed series of responses that are selected in a given situation, performers produce a unique motor solution to each individual situation that can be altered in an online manner (Sarpeshkar & Mann, 2011). It is proposed that early retinal information (from early ball flight) is an unreliable source of information, and that humans have difficulty estimating absolute distance and speed of an accelerating object from these sources (Bootsma & van Wieringen, 1990). As such, the precise prediction of ball arrival time and position required in the predictive control theory is near impossible, particularly when considering the ball may deviate in the air or off the pitch. Instead performers are thought to be able to constantly regulate their movements through up-to-date visual information in an online fashion, allowing skilled batsmen to use cues from later in ball flight to adjust their shot throughout its execution.

In their landmark study of table tennis players performing attacking forehand drives delivered by a ball projection machine, Bootsma & van Wieringen (1990) found two pieces of information supporting the use of prospective control and a strong perception to action coupling in fast ball sports. Firstly, the spatial location of the bat was found to be more variable at the point of impact than at the initiation of the bat swing, yet the variability of the direction of bat travel and its orientation decreased throughout the shot, and was discovered to be very low at impact. Secondly, the timing accuracy of the swing was found to be substantially more precise at the time of impact (derived from the bat direction of travel and rate of change at that point) compared to at the moment of swing initiation (calculated via the time-to-contact at that point). This is highlighted by the fact that bat swing time was inherently variable, and yet the smaller the time-to-contact at the initiation of the swing, the more acceleration was applied to the bat in the approach to impact. Negative correlations found throughout the swing between the mean acceleration of the bat and the time-to-contact also indicated that players were making adjustments to their swing from the time of initiation, and that at least two players were amending their swing during the second half of its execution. When considered together, these findings suggest the use of what the authors termed compensatory variability, where fluctuations in one execution variable are compensated for by varying another to guarantee the desired outcome, and a strong coupling between perception and action throughout swing execution.

Evidence for a coupling between perception and action was also found in simple catching tasks (Savelsbergh et al., 1991), where subjects were found to adjust their catching action, specifically the aperture of the hand, late in ball flight when catching both uniformly sized and deflating balls. A similar coupling was also found in baseball hitting (Ranganathan & Carlton, 2007; Katsumata, 2007), where the initiation and duration of the forward stride and weight transfer onto the front foot respectively were strongly coupled to the speed of the incoming ball. Both found the swing time of the batter to be related to ball speed (quicker for a fast ball), while Katsumata (2007) also discovered decreased temporal variability in the swing as it progressed towards impact. This suggests a compensatory relationship between the motion of the body and the bat swing in order to generate a successful impact, which is achieved through a strong coupling between the perception of ball arrival time and position and the action of creating the movement to intercept it.

Finally, the use of prospective control is also supported by the ability of skilled batsmen to adjust their strokes to account for unknown deviations in ball trajectory due to movement in the air (swing) or off the pitch (seam, spin, or bounce). This ability has been documented by Sarpeshkar et al. (2015), who noted that batsmen delayed almost every aspect of their movement when playing forward defensive shots against swinging deliveries compared to straight deliveries. The authors proposed that the increased spatio-temporal demands placed on a batsman when required to hit a swinging ball forced them to delay and shorten their movements, in order to assimilate additional visual information and guarantee a successful impact. If the control mechanism in this case were predictive, batsmen would be forced to approximate the exact arrival time and position, taking account of the future deviations due to ball swing, from early cues in order to gain a successful interception. Evidence from other sports such as soccer, however, shows that the human visual system is limited in its ability to predict the future arrival location of a laterally deviating ball from early cues alone (Craig et al., 2009), thus making a purely predictive control mechanism unlikely in cricket batting.

2.5 The Visual-Motor Delay

Whether the human uses predictive or prospective control to regulate movement, any system that responds to a stimulus to create motion must possess some form of delay. In humans this is known as the visual-motor delay; the time taken for the motor system to respond to the perceived visual stimuli and produce an adjustment to movement.

Several authors have attempted to quantify the duration of the human visual-motor delay in a range of sporting contexts, with findings suggesting that its length appears to depend on the subsequent manner in which the perceived information is used. Lee et al. (1983) suggested that the visual-motor delay can be as short as 100 ms when perceptual information is used to regulate an existing movement in an online fashion, finding delays of 55 – 130 ms in a simple hitting task, but can reach and exceed 200 ms when the perceptual information is used to produce more discrete movements such as initiation or large corrections.

The inertia of the object being used to make the interception also seems to have an effect on the measured visual-motor delay, with objects possessing larger inertia requiring more force and therefore more time to change direction. Bootsma & van Wieringen (1990) found variability in movement of a table tennis bat to be minimal from 105 – 122 ms before contact, suggesting this represents the visual-motor delay. Carlton (1992) found tennis players to adjust their swing responses to unexpectedly fast or slow bounces within 150-190 ms, while McLeod (1987) found cricket batsmen to take 190 – 240 ms to adjust to balls that deviated off small ridges in the ground. Although these two studies have been criticised for failing to take into account the time taken to change the impulse and direction of the heavy hitting objects, and in fact measure the time players take to correct an error in their swing rather than regulating and fine-tuning movement, they clearly indicate the presence of a substantial visual-motor delay in the human, suggesting that prospective control of movement right up to the point of impact is unlikely.

A shorter visual-motor delay has also been linked to expertise in fast ball sports (Le Runigo et al., 2005), allowing skilled performers additional time to assimilate information from ball flight before making a shot decision and executing the necessary movements. In this case expert tennis players were found to have shorter visual-motor delays than non-experts (161 ms compared to 221 ms) in a simple interceptive task.

2.6 Advocating a Hybrid Control Mechanism in Cricket Batting

Considering the short duration of ball flight for a cricket delivery (around 500 ms; Abernethy, 1981), and the presence of a visual-motor delay of around 200 ms to adjust the movement path of the bat (McLeod, 1987), perhaps the control mechanism for cricket batting is best viewed as a hybrid between prospective and predictive control. It is clear from the work discussed earlier (section 2.4), particularly the study of table tennis players done by Bootsma & van Wieringen (1990), that prospective control is the most likely control mechanism, but perhaps only up until about 200 ms before impact, after which the batsman is likely to have made a prediction for the future time and location of ball arrival (Sarpeshkar & Mann, 2011).

It is proposed that stimuli from the bowler's kinematics are interpreted along with early aspects of ball flight to give an idea of when and where the ball may arrive. This information is then compared to a previously learned internal representation of some target actions, in this case basic movements of the feet and body, providing the batsman with a framework upon which to base their shot. This action can then be regulated in an online manner based on up-to-date visual information up to a point around 200 ms prior to impact, by which time the batsman is required to have made a prediction of ball arrival time and location, as well as a final shot decision. It is feasible that skilled batsmen may be able to alter their movement within 200 ms of impact through fine adjustment of the wrists, thus controlling ball direction (Sarpeshkar & Mann, 2011) although it is thought that repeated fine motor training is required to develop the necessary skills to perform this action (Glazier et al., 2005).

Evidence of prospective and predictive control working in harmony is displayed by Katsumata & Russell (2012). Subjects were asked to hit a ball dropped from three different heights under full vision and partial occlusion conditions. Strong correlations between movement initiation and duration, and reduced timing variability through the swing from initiation to impact, suggest prospective control. However, the fact that movement onset was not impacted by occluding part of ball flight indicates that players do not need to be continuously coupled to vision of the ball, but can use a predictive model of what will happen based on acceleration timing information and their experience.

Further studies investigating the control mechanisms used for cricket batsmen are clearly required due to the lack of agreement and specific research in this sporting area. It is suggested that studies should continue to investigate differences in control mechanism between skilled and less-skilled players, particularly focussing on the abilities of truly elite players and whether they differ from the rest of the population. Research involving EMG of the muscles controlling movement at the wrist, elbow, and radioulnar joints may reveal the time frame in which batsmen are able to manipulate their movements based on up-to-date visual information. It is also crucial that future studies acknowledge the difference between adjusting an existing motor programme and correcting an error based on new perceptual information. In this regard researchers must attempt to maintain a high fidelity data capture environment, with appropriate visual cues and deviations in ball trajectory, in order to gain a realistic response from the batsman.

2.7 Movement Variability

No matter how many times we try, when executing a complex motor skill such as a cricket batting shot, humans never produce exactly the same movement (Bartlett et al., 2007; Preatoni et al., 2013). In fact, all movements a human makes are subject to innate kinematic variability, irrelevant of how skilled or familiar with the movement we are (Wilson et al., 2008).

2.7.1 Outcome and Movement Variability

Motor control research typically quotes findings on two different types of variability; outcome and movement variability. Outcome variability is the variability in the result of a movement, for example the post-impact ball speed or impact location on the bat face in a cricket batting shot. Typically, it is found that as skill level increases towards expertise, the variability in outcome decreases (Bradshaw et al., 2009). On the other hand, movement variability is the study of the variability in the movement dynamics that have produced the measured task outcome, for example joint angles and segment locations. It is critically important to distinguish between outcome and movement variability (Cohen & Sternad, 2009) and ideally form a link between the two.

Studies investigating this link have recently become more popular due to the advent of automatic marker tracking systems and software (James, 2004), as such making the investigation of multiple trials in three dimensions easier and more accessible to researchers. For example, Preatoni et al. (2009) showed race walkers to have very low variability for outcome parameters such as stride length and duration, but much higher variability for kinematic parameters related to technique such as joint angles. A number of studies however (Bradshaw et al., 2009; Egret et al., 2005; Coleman & Rankin, 2005) have failed to provide detailed kinematic analyses by investigating a low number of discrete outcome variables, failing to account for the kinematics of how the subject arrived at the measured position. Due to the many different coordination solutions available to solve any one movement problem (Newell & Corcos, 1993), analysing outcome variability alone doesn't give a full picture of the true variability of the athlete.

2.7.2 Theories of Movement Variability

Current literature suggests there are two opposing theories as to why variability is present in all human movements. Traditional motor control theory states that the nervous system is inherently noisy due to its complex nature, and that movement variability is unwanted noise in the system that should be minimised for skilled performance, while a more recent theory advocates that movement variability could be functional in helping humans adapt their movement strategies to changing external conditions and feedback from their surroundings (Langdown et al., 2012).

2.7.2.1 Movement Variability as Noise

Conventional control theory characterises variability in the movement system as unwanted noise that prevents the eventual outcome from matching the pre-planned motor programme, caused by redundancy in the sensorimotor system (Newell & Corcos, 1993). This is in line with the predictive theory of motor control (section 2.4.1) which suggests that humans replicate well learnt motor programmes, restricting the degrees of freedom within the sensorimotor system, in order to execute a given skill. In this theory, outcome variability and movement variability are both viewed as negative influences on performance, which can be reduced through relevant experience and practice. Since skilled performers typically exhibit low variability in outcome measures, it is assumed that expertise is associated with invariance in the movement pattern that produced that outcome.

In a study involving ball bouncing (Broderick & Newell, 1999), participants were asked to bounce a ball on a spot, and the kinematic patterns of each participant were analysed and compared. The authors found that as the amount of practice and experience gained by a participant increased, the level of variability in key kinematic factors decreased. Similarly, studies in baseball pitching (Fleisig et al., 2009) and the golf swing (Bradshaw et al., 2009) have found a linear relationship between skill level and variability, stating simply that the variability of selected kinematic variables at key instances in time decreased from lesser skilled to skilled athletes. This theory also states that humans possess a speed-accuracy trade-off, whereby as movement speed increases towards a maximal effort, the accuracy of that movement decreases through greater movement variability (Newell & Corcos, 1993).

Cohen & Sternad (2009) discussed the idea that movement variability consists of three components; noise in the motor system, tolerance (the margin for error present within the movement in order to maintain a successful outcome), and covariation (the ability of an individual to use redundancy to produce a more optimal solution). The authors found that as skill level increased, both noise and covariation decreased, while the tolerance afforded to the performer through their technique increased dramatically. It is therefore suggested that expert performers minimise the effects of the inevitable noise in the sensorimotor system by improving their ability to find the execution space which is least sensitive to any perturbations which may occur during the movement.

While some evidence supporting this theory is present in the literature, care should be taken in interpreting and applying these conclusions to future studies and complex human movements. Studies have primarily focussed on a small number of discrete measures, often simply assuming that if a performer is less variable in their outcome parameters or selected discrete kinematic variables at given time instants, they must be less variable in their kinematics throughout the movement. Also, despite the acceptance of some feedback control in more recent iterations of the theory (Schmidt & Lee, 2005), this theory fails to explain the spontaneous movement creation and adjustment made in very short time frames by expert performers to ensure outcome success.

2.7.2.2 Functional Movement Variability

More recently, ecological approaches to motor control have suggested the presence of movement variability could be functional, helping athletes to create flexible movement patterns and adapt to changing situations (Hamill et al., 1999; Bartlett et al., 2007), as well as learn new movements (Langdown et al., 2012). It is through the releasing of some of the degrees of freedom present in the sensorimotor system that, according to Bernstein (1967 – cited in Broderick & Newell, 1999), expert performance can be attained. This theory is in line with the prospective theory of motor control (section 2.4.2), whereby rather than having a pre-programmed set of responses that are selected from in a given situation, performers produce a unique motor solution to each individual situation, that can then be altered and updated in an online manner. Bernstein rejected traditional theories of movement variability, stating that due to the complexity of the human body, and the number of degrees of freedom available, the possibility of coordinating movements to be identical is impossible. Instead he suggested that a small change in the environment, or any of the small movements associated with a given action, brought about adaptations in the future action to reorganise the movement and achieve the desired outcome. This gives rise to a more up to date definition of functional or compensatory variability, where the presence of additional variability in certain aspects of movement allow stability and invariance in other, more important aspects, such as the eventual outcome (Hiley et al., 2013).

Shortly after the work of Bernstein, Arutyunyan (1968) investigated aiming accuracy in pistol shooting in both novice and expert marksmen. This study found that while experts had lower variability than novices in the position and orientation of the gun barrel, they also had increased variability in their arm movements specifically at the shoulder and elbow joints. This was the first study to look in detail at the link between outcome and movement variability, and provided some evidence that experts use compensatory variability (Preatoni et al., 2013; Langdown et al., 2012) to fine-tune an existing movement in order to adapt to environmental changes and optimise the outcome.

In their study of triple jumpers, Wilson et al. (2008) found a 'U' shape relationship between skill level and measured movement variability. The results showed that athletes of an intermediate ability were less variable in terms of kinematic features and ground reaction force outputs than both beginners and elite level performers. The authors proposed that beginners display high variability during the early phases of learning the movement as movement coordination patterns are acquired, and that coordination variability decreases as the movement is refined. The subsequent relative increase in variability between intermediate and expert level athletes was attributed to an increased flexibility in certain aspects of technique that allowed them to effectively cope with perturbations from the flight and impact of the previous phase of the jump, which for an intermediate level athlete may have caused a failure to complete the task.

A similar relationship between skill level and movement timing variability was found by Hiley et al. (2013) in an analysis of high bar giant circles. Expert gymnasts were found to have lower variability in the mechanically important aspects of technique than lesser skilled gymnasts, while demonstrating more variability in some of the less important aspects. This was interpreted as the elite gymnasts possessing a greater ability to utilise feedback control to correct for any perceived deviations in the mechanically important aspects of technique than their lesser skilled counterparts, ensuring high precision in the eventual outcome of the swing.

Evidence of expert performers exhibiting increased variability in less important kinematic aspects of technique, while maintaining relative invariance in the more important aspects of technique and outcome, has also been found in hockey (Franks et al., 1985) and cricket (Weissensteiner et al., 2011). Both studies found players to prioritise the maintenance of temporal consistency in the downswing phase of the swing, while varying the duration of the backswing in order to ensure this timing. Expert table tennis players were also found to exhibit compensatory variability to maintain an invariant timing of impact on a shot-by-shot basis (Bootsma & van Wieringen, 1990).

2.7.3 A Collaborative Theory of Movement Variability

In summary, previous research investigating the relationship between skill level and movement variability has found trends in both directions, suggesting that expertise is associated with both reduced and increased variability in various kinematic aspects of technique. Whilst these theories contradict each other, both agree that a reduction in outcome variability is strongly associated with expertise, and that measured movement variability decreases through the early learning stages of a movement as the athlete begins to adopt and refine a movement strategy. Hiley et al. (2013) suggest that whether this decrease in movement variability continues towards expertise (as in Broderick & Newell, 1999), or increases again to form the 'U' shape relationship found by Wilson et al. (2008), depends on the task being investigated. The authors propose that where precision is required, particularly in movement timing, variability appears to continue to decrease (Broderick & Newell, 1999), while in situations where adaptability to unexpected perturbations is required (Wilson et al., 2008) certain aspects of movement variability are seen to increase with expertise.

While the most logical complete theory is that certain critical variables, particularly outcome and end-point kinematics remain invariant for skilled performance, while other less important aspects experience variability via feedback control in order to achieve this, it seems unlikely that all variability in human movement is functional. The sheer complexity of the sensorimotor system and the number of degrees of freedom available in the body suggest that some aspects of movement must be prone to detrimental noise. This concept is supported by Cohen & Sternad (2009) who suggested that while detrimental variability (due to noise) decreases with practice, it is never entirely eliminated.

As such, a collaborative theory seems to explain the spontaneity of human movement creation and adaptation, while also taking into account the limits of the human sensorimotor system. While experts are likely to be able to increase the likelihood of task success through compensatory variability and feedback control of certain flexible aspects of technique, no level of familiarity or expertise can remove the inevitable presence of noise in the sensorimotor system and guarantee success. In practical terms regarding what this means to sports players and coaches, Glazier (2011) stated that practice should be a 'type of repetition without repetition', where the learner does not simply reproduce the same skill many times but attempts to solve the movement problem in a number of different ways. The performer is then more capable of executing their skill when faced with unexpected perturbations in the future.

2.8 The Kinematics and Kinetics of Batting

In comparison to the visual-motor control of hitting, the kinematics and kinetics of cricket batting has received relatively little attention in the literature. Batting provides a unique challenge in biomechanics due to its 'open' nature. This means that, not only are there constantly varying stimuli and uncertainties for the batsman, but also he can play any number of different shots to a given ball and achieve an outcome that is deemed successful. This fact has caused some authors (Sarpeshkar & Mann, 2011) to suggest that because of the substantial differences in technique and style between equally successful players, it is innately difficult to identify common biomechanical measures of success across groups of batsmen.

2.8.1 The Kinematics of Batting

Of the scientific studies on the kinematics of batting published to date, the vast majority have sought to establish the mechanics of the front foot drive against medium pace bowling with both skilled and unskilled batsmen. The front foot drive is probably the most common attacking shot used in cricket, and is inevitably the first shot taught to young players as they learn the game. This shot is played with a vertical bat to a ball of full length, whereby the batsman steps towards the ball and attempts to hit it in an aggressive manner back past the bowler along the floor (ECB, 2009). For the benefit of this review, and based on the work of Penn & Spratford (2011), the forward drive has been divided into six distinct phases (stance, preliminary movements, backlift and backswing, forward stride and downswing, impact, and follow through) that will be used to summarise previous studies and compare findings to the recommendations of three key coaching manuals (MCC, 1987; Woolmer, 2008; ECB, 2009).

No such work has been conducted on any back foot shot, and as such no review has been performed with a focus on the pull shot. The basics of each shot investigated in this research are outlined in section 3.9.2.

2.8.1.1 Stance

The setup and preliminary movements a batsman makes are critical to his future interception of the ball, as they allow him to take up the best position to both view and hit the approaching delivery (Stretch et al., 2000). Current coaching literature recommends an even distribution of weight between the front and back feet, which should be placed approximately shoulder-width apart, positioning the body in a completely or partially side-on position to the bowler (MCC, 1987; ECB, 2009). Elliott et al. (1993) and Stuelcken et al. (2005) found skilled and international batsmen respectively to display an even weight distribution between the front and back feet during the stance phase of the forward drive. Although research by Stretch et al. (1998) and Taliep et al. (2007) found the centre of mass to be positioned substantially forward of centre relative to the position of the feet, these studies were performed against medium-slow bowlers (21 m/s) delivering balls of a known full length, and playing shadow shots while watching video footage of a bowler's action respectively, thus their findings in this regard are less applicable due to their lack of realism to match task constraints. Stuelcken et al. (2005) also found nine international batsmen filmed during match conditions to exhibit a stance width of 0.46 ± 0.08 m, while also displaying an open stance with 26 ± 7° of shoulder rotation in the transverse plane (Figure 2.9). This is somewhat contradictory to the coaching recommendations, suggesting elite players utilise a wider and more open stance than is advised, perhaps in order to ensure a solid base to hit from, and a clear two-eyed view of the bowler without a large degree of head rotation.

Although these coaching recommendations and findings from the scientific literature make sense in theory, elite and highly successful batsmen display a wide array of positions and techniques in their stance (Figure 2.10), suggesting the body position at this time is largely redundant so long as the player occupies a good action position after any preliminary movements at the instant of ball release. Future work investigating the position of the batsman at the point of ball release should be undertaken, with a particular focus on the differences displayed in setup when facing deliveries of different lengths and from different delivery methods.

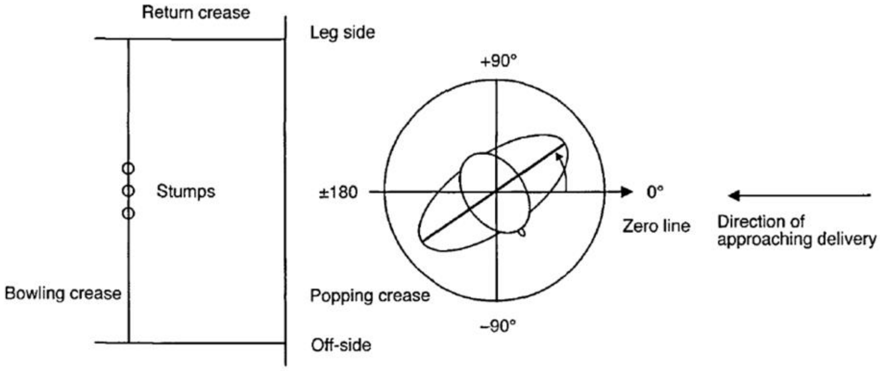


Figure 2.9: Angular displacement of a batsman's hips and shoulders in the transverse plane (adapted from Stuelcken et al., 2005).

Figure 2.10: Examples of different stance techniques used by elite batsmen (adapted from www.espncricinfo.com).

2.8.1.2 Preliminary Movements

The use of preliminary or trigger movements prior to ball release is an issue that receives a great deal of debate amongst coaches. While traditional coaching literature suggested the batsman stand still until the ball has been released (MCC, 1987), it has recently been proposed that preliminary movements provide batsmen with rhythm and 'unweights' the feet, enabling the batsman to get his momentum moving so as to be ready to move quickly forwards or back in response to the delivery of the ball (Woolmer, 2008). Sarpeshkar & Mann (2011) propose that by establishing this batting rhythm, batsmen may be more accurate in the timing of their foot movements in preparation for impacting the ball. This is supported by the perception to action theories presented earlier (section 2.4), suggesting that it is quicker and easier to modify an existing movement than to initiate a movement from a static position (Lee et al., 1983), indicating that some form of preliminary movement may aid in reducing the visual-motor delay experienced by cricket batsmen.

Three common preliminary movements exist according to Woolmer (2008; Figure 2.11); the forward press (front foot placed down the pitch towards the bowler), back and across (back foot placed deeper in the crease and towards the off stump), and a combination of the two (back foot then front foot both moved across to the off-side generating a widening of the stance). More recently players have begun to innovate and utilise variations on these three basic preliminary movements, for example moving both feet back into the crease, or moving the back foot forward before initiating a forward press.

Figure 2.11: Examples of the forward press (left) and back & across preliminary movements (adapted from www.swdcricket.co.za).

Stuelcken et al. (2005) found that amongst elite players the back and across preliminary movement was the most common, with seven out of nine international batsmen adopting this technique, while Dias & Ferdinands (2012) found seven out of eight grade club batsmen to utilise a forward press. Although both these studies used a relatively low number of subjects, they show a clear disparity in the techniques used between skill groups. While all three trigger movement techniques have justification for use, it is widely believed that the back & across method has more applicability to high level cricket, in an attempt to cope with the additional temporal constraints imposed by faster bowlers, whereas at lower ball speeds a batsman can afford to press forward and react accordingly (Woolmer, 2008). This view is supported by the work of Dias & Ferdinands (2012), who observed that batsmen utilising a forward press preliminary movement struggled to shift their weight backwards in preparation for a short pitched delivery, whereas the player who exhibited a back foot movement was able to move forward and back efficiently to play deliveries of a full and short length. The higher skilled batsmen in this study were also found to move significantly earlier relative to release than the lesser skilled players, suggesting a greater coupling to the release of the ball.

Although many coaches and authors have discussed and promoted the benefits of preliminary movements, it is conceivable that they may in fact harm a batsman's ability to effectively view the ball and move appropriately. It is thought that, whether a batsman utilises a preliminary movement or not, the head should be stable at the instant of ball release

(Woolmer, 2008; Sarpeshkar & Mann, 2011) in order to accurately interpret information from the bowler's kinematics and early ball trajectory. While some initial research has been conducted investigating some aspects of preliminary movements (Dias & Ferdinands, 2012), additional studies examining the effect of different movements on head position, centre of mass transfer, subsequent foot movements, and ultimately the quality of bat-ball contact would prove beneficial to the cricket coaching and research communities.

2.8.1.3 Backlift and Backswing

Although in existing scientific literature the backlift and backswing are generally phrases used to define the same movement (the backwards motion of the arms and bat before downswing), modern coaching literature (ECB, 2009) differentiates the two. In this case the backlift is viewed as the initial resting position of the bat, often prior to ball release, from which the backswing occurs, while the backswing is the final backwards and upwards movement of the bat immediately prior to the downswing. Coaching literature (MCC, 1987; Woolmer, 2008; ECB, 2009) recommends that the backswing should be initiated around the time of ball release, such that the backswing and downswing can be completed in one fluid motion. However, a number of elite batsmen have recently adopted a technique whereby the bat is raised prior to ball release, removing the need for a later backswing before the downswing. While this technique may have gained some support from players and coaches, it is likely to inhibit the batsman's ability to generate kinetic energy in the arm muscles via the stretch-shortening cycle when compared to a fluid motion from backswing to downswing (Sarpeshkar & Mann, 2011). This is thought to reduce the force and therefore bat speed a batsman is able to generate in the downswing, perhaps also hindering a player's ability to adjust their swing to any deviations in ball trajectory.

The majority of coaching literature (MCC, 1987; Woolmer, 2008; ECB, 2009) recommends a straight backlift and backswing, commonly stating that the longitudinal axis of the bat should not stray wide of second slip, such that it is easier for the bat to swing straight through the line of the ball. However, observation of many elite batsmen finds a range of different techniques (Figure 2.12), with the bat often being angled away from the body before looping back towards the line of the ball later in the swing. Stuelcken et al. (2005) and Taliep et al. (2007) both found batsmen to angle the bat away from their body during the backswing, reaching maximum angles of 47 ± 8° and 26 ± 16° to 27 ± 13° respectively (Figure 2.13), thus creating a looped bat path in the approach to the downswing. It has been suggested that this angle may create a natural resting position for the hands, and allow a fluid motion of the arms to generate bat speed in the downswing (Penn & Spratford, 2011).

Figure 2.12: A range of different backlift techniques adopted by elite players (adapted from Hurrion, 2008).

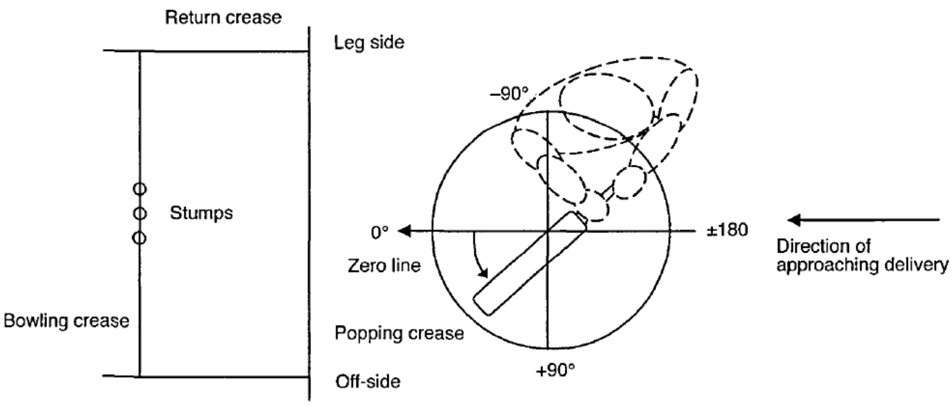


Figure 2.13: Plan view showing the two-dimensional angular displacement of the bat in the transverse plane during the backswing (adapted from Stuelcken et al., 2005).

Interestingly, and somewhat contrary to current coaching recommendations (MCC, 1987; ECB, 2009), Stuelcken et al. (2005) found elite batsmen to utilise a largely levered backswing about the wrists rather than a pendulum swing about the shoulders. The authors suggested that this allows the bat's centre of mass to remain closer to the body and thus the batsman's base of support, ultimately reducing the amount of energy and time required to manoeuvre the bat into the desired position during the downswing. This mechanical advantage gained by the batsman allows the batsman to initiate his downswing later, hence giving him more time to assimilate additional ball flight information before making a shot decision. Dias & Ferdinands (2012) found elite batsmen to exhibit a lower and more stable bat angle during their backswing, perhaps again allowing them to assimilate additional ball flight information before being forced to make a shot decision and initiate their downswing. As would be expected, the backswing was also found to be higher for the forward drive than the forward defensive (Stretch et al., 1998). Further investigation into the backlift and backswing techniques of elite batsmen could help establish the most effective techniques in order to generate high downswing speeds and forces, without losing the necessary accuracy and short downswing time to successfully bat against fast bowling.

2.8.1.4 Forward Stride and Downswing

Anecdotally, a critical part of successful batting in high level cricket is displaying decisive footwork in order to take up an optimal position from which the ball can be intercepted. Against full length deliveries, skilled batsmen were shown to exhibit a shorter forward stride when executing a forward drive than a defensive stroke (Stretch et al., 1998), and similarly a shorter stride with less knee flexion was used when playing an on drive compared to an off drive (Elliott et al., 1993). Although coaching literature recommends taking a shorter stride when playing forward drives or defensive shots on the leg-side (MCC, 1987), no advice is given on the magnitude of stride lengths or how this changes when playing defensively.

The initiation of the forward movement was found to occur later for the drive than the defensive shot (Stretch et al., 1998), the authors suggesting this not only allowed the batsman to gain additional information from ball flight cues, but also the shorter stride and increased flexion at the front knee provide a better fulcrum to transfer the batsman's centre of mass forward into impact when attacking the ball rather than defending. This transfer of momentum continued as impact approached, as batsmen were claimed to 'dip their heads forward' immediately prior to bat-ball contact (Stretch et al., 1998; Taliep et al., 2007). Interestingly, Taliep et al. (2007) also found the centre of mass and head of skilled batsmen to be significantly further forward throughout the shot than for lesser skilled players, perhaps indicating the position of the centre of mass during the drive as an indicator of skill. This is a recurring theme in the coaching literature (MCC, 1987; Woolmer, 2008; ECB, 2009), with all coaches highlighting the importance of weight transfer into the ball to generate bat speed and keep the ball on the floor after impact.

While few batting biomechanics studies have found specific traits that are able to distinguish skilled from lesser skilled batsmen, the coupling between the planting of the front foot and initiation of bat downswing has been found to be a key feature of expertise (Weissensteiner et al., 2011). Skilled players were found to initiate their downswing at the time of front foot stride completion, whereas lesser skilled players were less likely to form this link. The same relationship has also been found by Sarpeshkar et al. (2015) for skilled batsmen facing the swinging ball, indicating a strong coordination of the upper and lower body in the forward drive. Although both the studies of Weissensteiner et al. (2011) and Sarpeshkar et al. (2015) were both conducted in relatively realistic training environments while facing a bowling machine and the ProBatter machine respectively, the ball speed in both situations was relatively low (approximately 33 ms^{-1} for both), and the visual cues provided to the batsman were somewhat different to a match environment. This highlights the care with which these findings must be generalised to match batting performance, a fact emphasised by the work of Stuelcken et al. (2005), who showed that international batsmen in a match environment did not display this coupling, arguing that the time constraints and unknown length of the ball made it impossible to do so.

Similarly, existing studies have yet to come to an agreement regarding how batsmen generate bat speed in the forward drive or any batting strokes. Stretch et al. (1998) found evidence of segmental sequencing of front upper limb speeds during the downswing for 14 provincial batsmen, while Elliott et al. (1993) and Stuelcken et al. (2005) found peak segmental speeds to occur simultaneously, arguing that players placed more of an emphasis on timing and control rather than bat speed.

Further studies regarding the timing of movements during the batting action are required, with a particular focus on investigating the coupling of movements in a realistic performance environment, at realistic ball speeds, for a range of batting shots. Additional examination of the techniques used by batsmen to generate bat speed in their downswing should also occur across a range of shots, particularly given the increasing importance of short-format cricket, and the need for players to generate sufficient ball speed to clear the boundary throughout their innings.

2.8.1.5 Impact

At the point of impact, the batsman has three primary considerations; bat velocity, bat position, and bat orientation. While batsmen are traditionally, at least in attacking shots such as the forward drive, looking to maximise bat speed, they must also contend with the spatial constraints of making contact with the ball in the centre of the bat, and orientating it so the ball successfully avoids the eleven opposition fielders. As a result, cricket batsmen are found to generate lower bat speeds than in other striking sports such as baseball and tennis (Welch et al., 1995; Mitchell et al., 2000), probably due to the need for control over speed, and the relatively large inertia of a cricket bat. Stuelcken et al. (2005) found peak bat speeds around 21.2 ms^{-1} 0.02 s before impact, suggesting highly refined timing of the swing to the flight of the ball, although the accuracy of digitisation in this case, and the relatively low frame rate used (250 Hz) call this timing somewhat into question.

As in the downswing, at impact skilled batsmen are found to position their head further forward than lesser skilled batsmen (304 mm vs. 193 mm); this leads their centre of mass further forward and aids efficient momentum transfer into the stroke (Taliep et al., 2007). The authors also found the head position of the batsman to be positively correlated with whole body centre of mass position throughout the shot, giving support to coaches' recommendations to position the head forward of the centre of mass in order to transfer momentum into impact (MCC, 1987; ECB, 2009). Skilled batsmen were also observed to angle their bat downwards at the time of impact to ensure the ball is hit down and they cannot be caught (Stuelcken et al., 2005); this further highlights the prioritisation of control over speed. Future studies should further investigate the body positions of batsmen at the point of impact, with a particular focus on the position of the centre of mass and the head. Researchers should attempt to identify differences between elite and lesser skilled batsmen in a more realistic performance environment, and any differences according to the speed or delivery method of the ball. Further investigation of the interaction between the batsman and bat should also be conducted, with a particular focus on the influence of physical bat characteristics such as mass and inertia on swing kinematics and timing.

2.8.1.6 Follow Through

The follow through serves two purposes; firstly, to ensure the limbs have sufficient time to decelerate avoiding injury, and secondly to make certain that the force generated in the downswing is efficiently transferred to the ball (Sarpeshkar & Mann, 2011). There are two distinct follow through techniques utilised for the forward drive; the full follow through and the checked follow through (Woolmer, 2008; Figure 2.14). Stuelcken et al. (2005) found that the majority of elite batsmen assessed in their study preferred to use a checked follow through as opposed to the full alternative, although the effects of this technique on bat speed at the time of impact have not been investigated. It is also possible that the increased bat and arm deceleration required to achieve a checked follow through may give rise to repetitive strain injuries such as lateral epicondylitis (Penn & Spratford, 2011), although this has not yet been directly investigated. Future studies examining the reasoning behind the choice of follow through technique for a given shot should be carried out, with particular focus on the line and length of the delivery and the bat speed around the time of impact.

Figure 2.14: Examples of the full (left) and checked (right) follow through techniques (adapted from www.espncricinfo.com).

2.8.1.7 Determining Shot Success

In assessing the success of a batting shot, researchers have a number of options available to them. A number of batting kinematics studies (Elliott et al., 1993; Stretch et al., 1998; Stuelcken et al., 2005; Taliep et al., 2007; Cork et al., 2010) focus on pre-impact bat and/or post-impact ball speed as a measure of shot success. While this provides some indication of the overall shot success, the post-impact ball speed in particular also depends heavily on the impact location of the ball on the bat (Bower, 2012). In an attempt to account for this, a simple categorical measure of the quality of bat-ball contact was implemented and validated for use by Muller and Abernethy (2006; 2008), consisting of live categorisation of each impact by a trained observer into good, bad, and no contact groups according to the resulting ball trajectory. This method was then used by Muller and Abernethy (2006) and Weissensteiner et al. (2011) to examine differences in interceptive ability between highly skilled and lesser skilled groups in a number of batting scenarios. While this approach provides researchers with a method by which they can quantify impact quality, it still gives minimal insight into the exact impact location of the ball on the bat face, merely indicating whether a batsman hit the ball on the face of the bat, on the edge, or missed it altogether.

In the only cricket studies to physically measure impact location, McKellar et al. (1998) and Stretch et al. (2004) placed a grid of piezoelectric sensors on the bat face in a 7 x 23 square grid. Although this allowed them to quantify impact location with high accuracy and resolution, the fitting process is complex and time consuming and therefore cannot be applied to each subject’s bat in turn, instead relying on a standard instrumented bat for testing. This is problematic particularly in elite cricket, as players become heavily accustomed to a bat with specific weight and balance characteristics, thus a standard bat may affect their swing mechanics. In golf and tennis studies respectively, impact location has been measured using pressure sensitive impact stickers (Hocknell, 2002) and high-speed video analysis (Knudson, 1991; 1993), although these are both time consuming in their application and processing stages.

More recently, in a study investigating the effects of off-centre impacts on racket and wrist kinematics in tennis, Hau (2013) calculated from motion capture data the frame at which the ball was closest to the racket, and subsequently used positional data from this frame to transform the ball location onto the local coordinate system of the racket, and hence calculated the impact location. Due to the relatively fast capture rate (480 Hz) used in this study, and the longer impact durations found in tennis (4.4 – 6.2 ms; Haake et al., 2003), impact is less likely to occur between frames, thus reducing the possibility of errors in estimating impact timing and location. However, the shorter impact durations in cricket (1.0 – 1.5 ms), and the slower capture rates used in existing batting kinematics studies (< 250 Hz; Stuelcken et al., 2005; Taliep et al., 2007; Dias & Ferdinands, 2012; Peploe et al., 2014), mean that this protocol is unsuitable for use in a cricket batting scenario.

In the most appropriate study for application to cricket batting published to date, Betzler et al. (2012) developed a method for determining the impact location of a stationary golf ball on the clubface of a driver. Five Qualysis motion capture cameras (1000 Hz) captured the position of one marker on the ball and three spherical reflective markers placed on top of the clubhead, which were in turn used to calculate the position of four virtual markers around the perimeter of the clubface. The clubface was then treated as part of a sphere with radius 254 mm to account for its curvature, and the exact timing of impact determined as the time at which the distance between the centre of the clubhead sphere and the ball centre dropped below 254 mm plus ball radius, using an iterative cubic best fit extrapolation of the clubhead position to calculate between frames. A similar extrapolation tool was used to determine the position of the virtual clubface markers at the time of impact, as such allowing impact location to be assessed. Direct comparison of the calculated impact location from the model with the actual impact location, established using impact spray on the clubface, revealed mean offsets of 2.1 ± 1.5 and 1.7 ± 1.4 mm in the horizontal and vertical directions respectively. While this study clearly demonstrates a high level of accuracy in determining impact location using a curve fitting methodology, the pre-impact movement of the ball, and the assumption that the bat represents part of the circumference of a sphere not being applicable, make this method of calculating impact timing and therefore impact location unsuitable for application to cricket batting. Future studies should develop a methodology for accurately determining the impact location of a cricket ball on the bat face alongside capture of full body kinematics in a realistic training environment, in order to begin to relate aspects of technique to shot success. Clearly the specific bat selected by each batsman is also likely to have an influence on shot success. Although outside the remit of this study, future studies should attempt to quantify bat physical characteristics and performance, and assess their impact on shout outcome in terms of post-impact ball speed and direction.

2.8.1.8 Summary and Limitations

Existing research regarding the biomechanics of cricket batting has been discussed. Findings are presented for the kinematics of the front foot drive in six stages, from stance to follow through, highlighting the findings of a range of authors compared to modern coaching theory. While these aspects of biomechanics in cricket batting have received moderate attention in the literature, there are a number of limitations to the studies examined above. In general, these studies have investigated the mechanics of front foot defensive and drive shots with no consideration of any other shots for example off the back foot. There is also little attention paid to the interceptive and anticipatory skill of the batsman, and no relation of certain mechanics to shot success or quality of bat/ball contact.

When interpreting existing results is vital to consider the context and environment that the study has been conducted in (lab, training, or match environment). Investigations conducted via video simulation in a lab environment, while they may allow greater control and higher levels of measurement accuracy, do not replicate the specific task constraints of match play well, and as such the realism of the batsman’s movements may be compromised. Similarly, in a match environment the task constraints and environment are realistic, but the level of control and accuracy in measurement is substantially reduced due to the open nature of the game and lack of ability to instrument the players.

This difference in environment and the effects it has on batsman response is perhaps best highlighted via a comparison of the work by Stuelcken et al. (2005) and Taliep et al. (2007). While Stuelcken et al. (2005) used two-dimensional video footage to analyse batsmen in a match environment (Figure 2.15), Taliep et al. (2007) used video simulation techniques in a lab and three-dimensional motion capture software to assess differences between shots and players of different skill. Although the player ability level and shots played in each study are comparable, the results in terms of movement timings, speeds, and magnitudes are vastly different. This innate difference is emphasised via the difference in peak bat speed found during the downswing; where batsmen in the lab only reached a maximum linear endpoint speed of 11.1 ms^{-1} in the lab environment (Taliep et al., 2007), as opposed to 21.2 ms^{-1} in a match environment (Stuelcken et al., 2005). These differences stress the importance of a realistic performance environment with accurate task constraints and the intent to actually intercept the ball in future biomechanics and motor control studies.

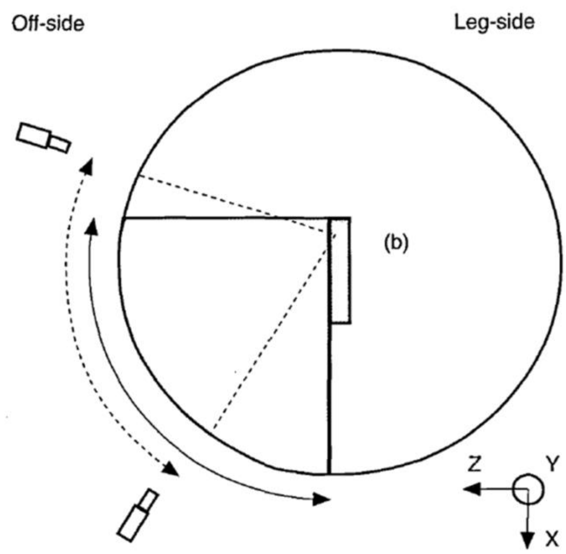


Figure 2.15: The setup used by Stuelcken et al. for analysis of batsmen in a match environment, showing camera location (dotted lines) and the direction of drives played (solid lines) (adapted from Stuelcken et al., 2005).

As with the interceptive skill and anticipation studies discussed earlier, a number of the biomechanics investigations rely on a bowling machine for ball delivery. This has a detrimental effect on the validity of task constraints and cues presented to the batsman, who would ideally be faced with a bowler for an exact representation of the batting task, and to be able to mimic the movement coupling he would normally exhibit. However, as with performing testing in a lab environment, the use of a bowling machine provides accuracy and repeatability to the delivery of the ball. This trade-off between realism and control must be assessed in detail before decisions are made regarding the content of future studies.

Other limitations with existing studies are with regards the players and sample sizes used in testing. Only one study has attempted to understand the movements of elite international batsmen; Stuelken et al. (2005) who analysed the two-dimensional mechanics of just one front foot drive from each of nine batsmen. Other studies have generally used a small number of batsmen and a low numbers of trials, perhaps giving less support to their conclusions as being applicable to the wider playing community. The use of international bowlers and bowling speeds is also an area lacking significant investigation; the temporal demands of facing a 90 mph (40.2 ms^{-1}) bowler are far greater than facing someone at 70 mph (31.3 ms^{-1}) or 80 mph (35.8 ms^{-1}), and thus it is likely the movement patterns and techniques of batsmen will be different. Finally, none of the previous studies have examined in detail the coupling of biomechanical movements to key events in the flight of the ball, for example release, bounce and impact; this could easily prove to be a key aspect of expertise.

Overall, while there has been some research regarding the biomechanics of batting, there is significant room for improvement and future studies investigating different aspects of batting biomechanics. A number of these biomechanical studies are also criticised for over complicating their results such that they are of little use to coaches and players (Penn & Spratford, 2011); this is something that must be addressed in future research.

2.8.2 The Kinetics of Batting

Even in comparison to studies of batting kinematics, the kinetics of cricket batting has received sparse coverage in the literature. Three studies of grip forces in batting have been performed (Gibson & Adams, 1989; Stretch et al., 1995; Stretch et al., 1998). In an investigation between front foot drive and defensive Gibson & Adams (1989) found that, for a given player the initial grip pattern of the drive and defensive strokes were similar, however changed as the shot decision was made such that a tighter grip was exhibited for the drive. They suggested this was to allow and account for the greater bat speed generated during the forward drive. Stretch et al. (1995; 1998) found the top hand to be dominant in the forward drive, as recommended by coaching literature (MCC, 1987; Woolmer, 2008; ECB, 2009). The bottom hand was then shown to reinforce around the time of impact. Interestingly, grip forces were found to be highest either side of impact (to control the large centrifugal force generated by the swing of the bat), but lower at the point of impact itself (Stretch et al., 1995; 1998). This is similar to findings in golf (Shibayama & Ebashi, 1983) and baseball (McIntyre & Pfautsch, 1982), where it is suggested the relaxed grip at impact is the brain subconsciously preparing the muscles for impact. Interesting future studies may investigate the grip forces of elite and non-elite batsmen in different strokes or different types of delivery, and also the effect of different grip techniques on bat path and speed.

Only one study (Dias & Ferdinands, 2012) has investigated the weight distribution and ground reaction forces produced by batsmen throughout their action. The higher skilled players in this study were found to have a more even weight distribution at the start of their initial movement (62.7% on the back foot compared to 89.9% for the lesser skilled batsmen), and as such were believed to be able to effectively shift their weight more easily either forwards or back depending on the type of delivery. The ground reaction forces were then used to assess the type of preliminary movement used by each batsman. Unfortunately, no further results were published in this preliminary study, and as such no further conclusions could be drawn. Future studies investigating the weight distribution of batsmen, and the subsequent preliminary movement and shot played under a range of different ball delivery method, speed, and length conditions are required to better understand how skilled batsmen position their weight and transfer momentum into each shot, such that key principles of expertise can be extracted and applied in coaching at all levels.

2.9 Endpoint Speed Generation in Hitting Sports

As well as gaining an understanding of existing studies of cricket kinematics and kinetics, it is also useful to explore the techniques and kinematics used to generate speed in other hitting sports such as baseball, golf, and tennis. Given the lack of agreement in existing research regarding how batsmen generate bat speed in the forward drive (section 2.8.1.4), and the absence of studies investigating other batting shots, particularly those where generating maximum ball speed is seen as critical to success, findings from other hitting sports should be used as a basis for further examination of this area.

A number of kinematic and kinetic variables have been linked to an increase in clubhead speed during the golf swing. Cooper and Mather (1994) found that the timing of peak clubhead speed varied according to skill level, with elite golfers peaking at the time of impact, while high-handicap golfers peaked significantly earlier in the downswing. The angular separation between the pelvis and upper thorax in the transverse plane (often referred to as the X-factor in golf; Mclean, 1992) has also been strongly linked to clubhead speed (Cheetham et al., 2001; Myers et al., 2008; Chu et al., 2010). Mclean (1992) proposed that the difference in rotation between the pelvis and upper thorax at the top of the backswing was more important than absolute shoulder turn, finding that long hitting professional golfers had an X-factor significantly larger than short hitting professionals. More recently Cheetham et al. (2001) identified the increase in X-factor during the downswing caused by early pelvis rotation (referred to as the X-factor stretch) as more important than the X-factor at the top of the backswing, and found professional golfers to have a significantly greater X-factor stretch (19%) than amateur players. This X-factor stretch is an example of golfers exploiting a stretch-shortening cycle, whereby an active stretch of a muscle/muscle group (eccentric contraction) is followed by an immediate shortening (concentric contraction). In the case of the golf swing, this helps generate additional speed of movement, as elastic energy stored by the muscles during the coiling phase (caused by further separation of the pelvis and thorax segments) is stored and released during the uncoiling downswing phase.

Low-handicap golfers were found to employ greater and quicker weight shift of the body back towards the back foot during the backswing, then forwards towards the lead foot in the downswing than their high-handicap counterparts (Wallace et al., 1990; Koenig et al., 1994; Chu et al., 2010). This was suggested to assist in generating additional clubhead speed during the downswing via increased momentum generated by motion of the body. Chu et al. (2010) also found a rapid reduction immediately prior to impact in the ground reaction force produced by the leading foot to be advantageous to generating clubhead speed, suggesting an upward pull in the approach to impact generated by the motion of the whole body should be applied. This is supported by the work of Welch et al. (1995), who found professional baseball hitters to exhibit front knee extension in the approach to impact, pushing the front hip backwards and acting as a block around which the body can rotate.

Chu et al. (2010) also found an increased lateral bending of the trunk towards the trailing side during the downswing and a high degree of trunk forward tilt in the approach to impact to be strong predictors of ball speed, proposing a conditioning regime focussed around training the core as being critical for success (supported by the work of Lephart et al., 2007). Similarly, the cocking and uncocking of the wrists has been found to significantly increase clubhead or baseball bat speed (Robinson, 1994; Welch et al., 1995; Chu et al., 2010). Robinson (1994) actually found that the degree of wrist cocking was the strongest determinant of clubhead speed in a linear regression study between golfers of varying ability, accounting for 60.3% of the variance.

The importance of the kinetic chain for endpoint speed generation in hitting sports has also been well documented, for example in golf (Hume et al., 2005), baseball (Welch et al., 1995; Escamilla et al., 2009a), and tennis (Elliott, 2006; Fleisig et al., 2003). Hume et al. (2005)

describe the golf swing as a 'powerful stretch shortening cycle activity, in which the muscles of the lower, mid-section, and upper body are rapidly stretched before shortening'. Chu et al. (2010) found evidence of the kinetic chain in the golf swing, suggesting that the rapid acceleration then deceleration of large body segments should occur before impact such that energy can be transferred to the more distal segments and clubhead. Escamilla et al. (2009a) found skilled baseball hitters to exhibit sequential peak angular velocities in the pelvis, torso, and then the elbow in the approach to impact. Further evidence of the kinetic chain in baseball hitting was found by Shaffer et al. (1993), who used EMG to demonstrate the fact that muscular activity in baseball hitting began in the lower body before progressing to the trunk and upper body. Skilled hitters also took longer in the stride phase of the swing (Escamilla et al., 2009a), with the authors suggesting an increased load-up action, as well as displaying greater peak upper torso angular velocity, lead elbow and lead knee extension than lesser skilled hitters. This was all suggested to contribute towards a greater post-impact ball speed, most likely as a result of increased bat speed. The extension of the lead elbow (Escamilla et al., 2009a) and wrists (McIntyre & Pfautsch, 1982) during the swing phase were also found to be adjusted in order to ensure suitable bat orientation at impact.

Future studies should investigate the generation of bat speed and post-impact ball speed in cricket, in an attempt to understand the mechanisms used by elite players when hitting. It is critical that investigations distinguish between situations where a batsman prioritises speed over control as opposed to prioritising control over speed (as in Elliot, 2006), as it is likely that the mechanisms for generating bat speed will be different in each scenario.

2.10 A Multidisciplinary Approach to Batting Research

As suggested in previous literature review sections, it is apparent that the skill acquisition and biomechanics aspects of research complement each other well, and both contribute to a holistic understanding of expertise in cricket batting. The absence of consideration for either of these disciplines could easily devalue the results gained from any future study. For example, a biomechanical study not providing appropriate cues to a batsman in a realistic performance environment loses some applicability to match situations. Similarly, interceptive studies are often lab based, simulated timing tests that lack task specificity to batting movements and the intent to intercept a moving ball; these would benefit from some specificity to cricket batting task constraints in order to gain more realistic results. A number of the studies in both disciplines would also benefit from more robust biomechanical measurement design; for example, using two-dimensional video data with a relatively low frame rate to measure complex kinematic features of movement (Stuelcken et al., 2005; Pinder et al., 2009; 2011a) may not give an accurate picture of the movement executed, and hinders the researcher in gaining all the available and desired information. In this case a three-dimensional assessment would have produced far more robust findings, and provided additional measurements for analysis. By combining knowledge of these two research disciplines, a far greater understanding of batting skill could be achieved.

Despite the logic behind this multidisciplinary approach, and the previous recommendations for it in various publications (Stretch et al., 2000; Penn & Spratford, 2011), there has been little effort to integrate knowledge of motor control concepts with biomechanical measurements. To date just one published paper has made this effort in a cricket batting scenario (Weissensteiner et al., 2011). In this study the authors investigated to what extent the differences in interceptive ability between skilled and lesser skilled batsmen are attributable to the durations of various movement components in a batting stroke and the timing or sequencing of swing kinematics relative to ball release, bounce and impact time. This was investigated by putting batsmen through a batting skills test (from Weissensteiner et al., 2009) performing front foot drives into various targets against a bowling machine. Difficulty was then increased by performing the test again using ½ and ⅓ width bats. Two orthogonal high-speed cameras captured the movements of the batsmen, and a trigger in the bowling machine was used to mark the time of ball release. While this method does use a bowling machine and thus unrealistic visual cues, the experimental design gives far more consideration to aspects of interceptive skill and batting specific task constraints, with a fairly robust biomechanical measurement protocol.

Weissensteiner et al. (2011) initially found the task to successfully demonstrate systematic differences between skilled and lesser skilled batsmen in relation to both task performance and interceptive movement organisation. In terms of task performance skilled players were more accurate in shot positioning in both full and ½ width bat conditions; there were no significant differences found in the ⅓ bat width condition as this was deemed too spatially challenging for even the most skilled batsmen. Interestingly there were no differences found in the quality of bat/ball contact between skilled and lesser skilled batsmen; although this was only assessed in terms of good contacts, edged or missed deliveries. With regards to the timing of movements, skilled players were found to initiate and complete their forward stride earlier and couple the commencement of their downswing to the point of stride completion. Skilled players also showed low variability with respect to the timing of downswing initiation relative to the time of impact, although no differences in downswing speed or duration were found between the two skill level groups. The authors also found skilled batsmen to exhibit far more consistent temporal sequencing of shots than lesser skilled players, suggesting an aspect of well-learnt motor skills in expert shot execution.

Although a number of aspects of this study, including the use of a bowling machine and the pre-release knowledge of approximate ball bounce location, question its results in terms of their applicability to a match environment, it goes some of the way towards developing a more accurate, realistic, and robust method for the capture of biomechanical measurements of a cricket batsman. As a result of this study, Weissensteiner suggests that batting expertise is perhaps characterised by enhanced shot positioning and movement timings coupled to the delivery, as opposed to bat speed or even the quality of bat/ball contact. This provides an excellent starting point from which to develop further studies considering aspects of interceptive skill and anticipation alongside batting specific task constraints and accurate biomechanical measurements of batting kinematics and shot success.

2.11 Chapter Summary

Previous research into cricket batting has predominantly focussed on either anticipation and visual strategy, or the kinematics of the forward drive shot. While the control mechanisms and visual strategies for hitting are now relatively well understood and documented, there is a general lack of research and agreement on the kinematic features of successful batting shots and techniques used by expert batsmen. Existing biomechanical research often simply presents kinematic findings for a small sample of batsmen with various playing abilities hitting forward drives, in an unrealistic performance environment, usually with no consideration of the specificity to accurate task constraints required to gain an accurate and realistic response, or the resulting success of the shot. This study will develop a novel methodology for capturing the three-dimensional kinematics of cricket batsmen in a realistic training environment, such that the movement patterns of elite batsmen against fast bowling can be assessed in a range of conditions and playing a range of different shots, and coaching practices and recommendations evaluated and reassessed.

CHAPTER 3

METHODS 1 – DATA CAPTURE

3.1 Chapter Outline

This chapter illustrates the process used in capturing the necessary kinematic data for detailed three-dimensional analysis of batting technique. It begins by discussing the challenges faced when attempting to track the movements of a cricket batsman, and justifies the selection of a suitable motion capture system. It then presents how the challenge of tracking a batsman was successfully achieved through innovative marker set design, before outlining the experimental setup, testing protocol and subjects used in data collection.

3.2 The Challenge of Tracking a Human Batsman

Measurement of the human in a realistic batting environment provides several challenges to the researcher. Firstly, batting is an open, reactive skill with a range of different shots and techniques to account for in a measurement protocol. With no fixed aspects of movement, bat or ball locations; motion capture and movement definition become difficult. Secondly, different to a fast bowler in cricket where three-dimensional motion capture has been heavily used in the past (Ranson et al., 2009), batsmen wear bulky personal protective equipment that often covers key landmarks commonly used in other motion capture studies (Vicon, 2012a). Finally, the nature of batting requires that either a netted area that may disrupt measurement signals is used to contain the ball, or equipment is setup far away so as to avoid hampering the natural actions of the batsman, or being damaged by a fast moving ball.

As such, previous batting biomechanics studies have either used manually digitised video capture to monitor a batsman's movements in a match or training environment (Stretch et al., 1998; Stuelcken et al., 2005), or three-dimensional motion capture of a batsman playing a shadow shot to a video screen of a bowler delivering a ball (Taliep et al., 2007). The use of the video screen method lacks specificity to the realistic task constraints, and the intent to intercept found in a match or training environment, and as such produces vastly different batsman movement patterns and timings in comparison to when facing a live bowler

(Sarpeshkar & Mann, 2011; Penn & Spratford, 2011). While the use of digitised video in a match or training environment maintains the appropriate task constraints, visual cues, and movement patterns for the batsman, the information gained has several limitations. Firstly, the majority of previous video studies only capture two-dimensional data of the batsman's kinematics, often neglecting movements in the sagittal plane (Stretch et al., 1998; Elliott et al., 1993). Those studies utilising two cameras to gain three-dimensional data (Stuelcken et al., 2005) overcome this downfall, however their accuracy can be called into question due to the innate difficulty of digitising a batsman; batting equipment makes joint centre location tricky, unavoidable aspects of human error exist, and the fact that the frame rate it is possible to analyse is relatively low.

As such, in an attempt to keep both task constraints and visual cues realistic, whilst maintaining robust biomechanical measurement protocols, it was decided that a three-dimensional marker-based motion tracking system would be used for testing in a realistic netted training environment.

3.3 Selecting a Motion Capture System

Having disregarded the use of digitised video to capture kinematic data due to its low accuracy and time consuming nature, two primary three-dimensional motion capture systems remained for consideration. These included Vicon (Vicon Motion Systems, Oxford, UK) which is a passive marker system relying on spherical retro-reflective markers placed on joint centres and functional landmarks being identified and tracked by a number of infra-red light emitting cameras, and Coda (Codamotion) which is an active marker system relying on miniature infra-red markers again placed on joint centres and functional landmarks, each with their own known identity, being tracked by several Coda sensor units in three dimensions. In both systems, three-dimensional marker locations are computed from the images recorded by surrounding cameras using triangulation algorithms. These systems were selected due to availability within the department, and the fact that both methods allow the tracking of a large number of individual markers as well customisation of marker sets and segment definitions to suit the movements performed.

Each system has distinct advantages and disadvantages over the other. While the Vicon passive marker system uses small retro-reflective spheres attached with tape to the body, the

Coda system requires larger battery packs and wiring in order to emit the infra-red light from the active markers; this makes it more cumbersome and its functionality threatened by a fast moving cricket ball. However, unlike the Coda active marker system in which each marker has its own unique identity and is tracked as such, the Vicon passive marker system often suffers from processing difficulties and marker swapping, as all passive markers appear identical on the software; this makes for an increased processing time manually labelling and correcting trials. Although the processing of Vicon may take additional manpower, Coda only allows a maximum of 54 markers to be tracked at any one time, and as the numbers increase above 16 the temporal resolution of the current system available drops; this lower number of markers makes it more difficult to use for complex full body data. As a result of this information, the Vicon passive marker system was selected as the primary method of motion capture for this project as, although it may take additional processing time and input, it is far less cumbersome and inhibits the natural batting action considerably less than Coda, as well as allowing an unlimited number of markers to be tracked at full resolution giving a more thorough picture of full body motion.

3.4 Marker Set Design

3.4.1 Development of the Lower Body Marker Set

As mentioned previously, there are two main problems surrounding the use of Vicon motion capture for cricket batsmen in a realistic training environment. Firstly, the batting area has to be surrounded by netting to avoid the ball damaging measurement equipment. Initial pilot testing performed in the ECB National Cricket Performance Centre (NCPC) found that the use of lightweight netting was sufficient to stop the ball and did not hamper the measurement capabilities of the Vicon cameras, hence rectifying any potential issues with using a netted area.

However, the batting protective equipment commonly worn by all batsmen obscured several key marker locations used in standard Vicon setups (Vicon, 2012a) particularly around the knee and ankle joint (Figure 3.1). Two possible solutions to this problem were identified; either placing markers on the leg guards themselves or using clusters of markers placed elsewhere on the leg to interpret joint centre locations previously determined in a static trial.

Figure 3.1: Ankle and knee joints obscured by batting leg guards.

3.4.1.1 Cluster Marker Method

Cluster markers as a technique for tracking joint centres have been used in a number of previous kinematic studies (Chin et al., 2009; Elliott et al., 2007; Schmidt et al., 1999) primarily for measurement of the upper and lower arm segments. In fact, Elliot et al. (2007) found the error produced using a cluster method when tracking the known positions of a mechanical arm to be lower than those found when using a joint centre marker method. However, other studies have found significant errors in cluster marker methods due to changes in cluster alignment and muscle/skin artefact during movement (Yeadon & King, 2015). The effectiveness of each method in this application was assessed independently through the analysis of joint positions, angles, and separations in a range of simple movements including squats and lateral leg swings.

In order to examine the accuracy of a cluster method in this application, the pelvis and one leg of a single subject were markered with both joint centre and cluster markers. Cluster markers were placed on the back of the leg due to the presence of the leg guards on the front. Two different versions of the leg were then defined based on the joint centre and cluster markers (Figure 3.2) and the joint positions, angles and separations were analysed using Visual 3D biomechanics software (C-Motion Inc.).

Raw marker position data, captured at 250 Hz, was initially interpolated to fill any small gaps (maximum gap size interpolated = 10 frames; 40 ms) where markers had fallen out of view, then filtered using a low-pass Butterworth filter with a cut-off frequency of 15 Hz (determined using the residual analysis method proposed by Winter (2009)) (Figure 3.3).

Joint positions, angles and separations for the ankle, knee and hip joints were then compared for cluster and joint centre marker methods, and also compared to digitised video data acquired from the same trial as a control measure.

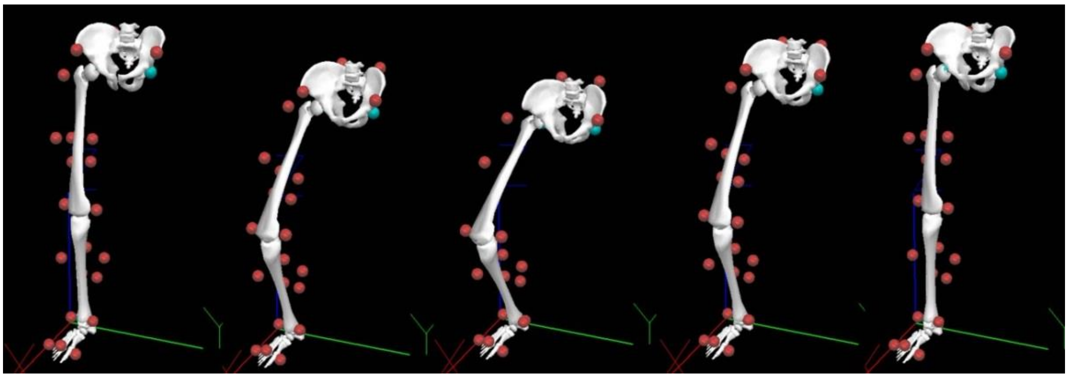


Figure 3.2: Visual representation of a squat based on the Visual 3D model, where one leg is markered for both joint centre and cluster marker definitions.

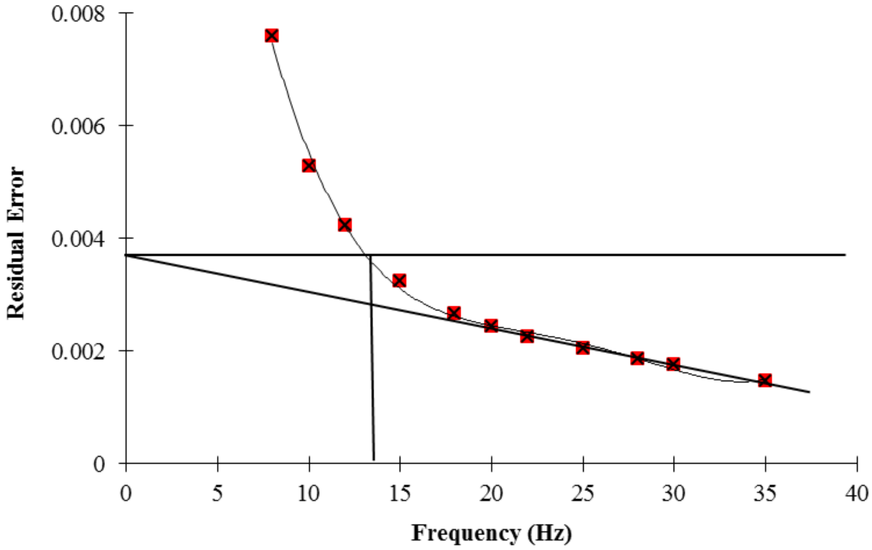
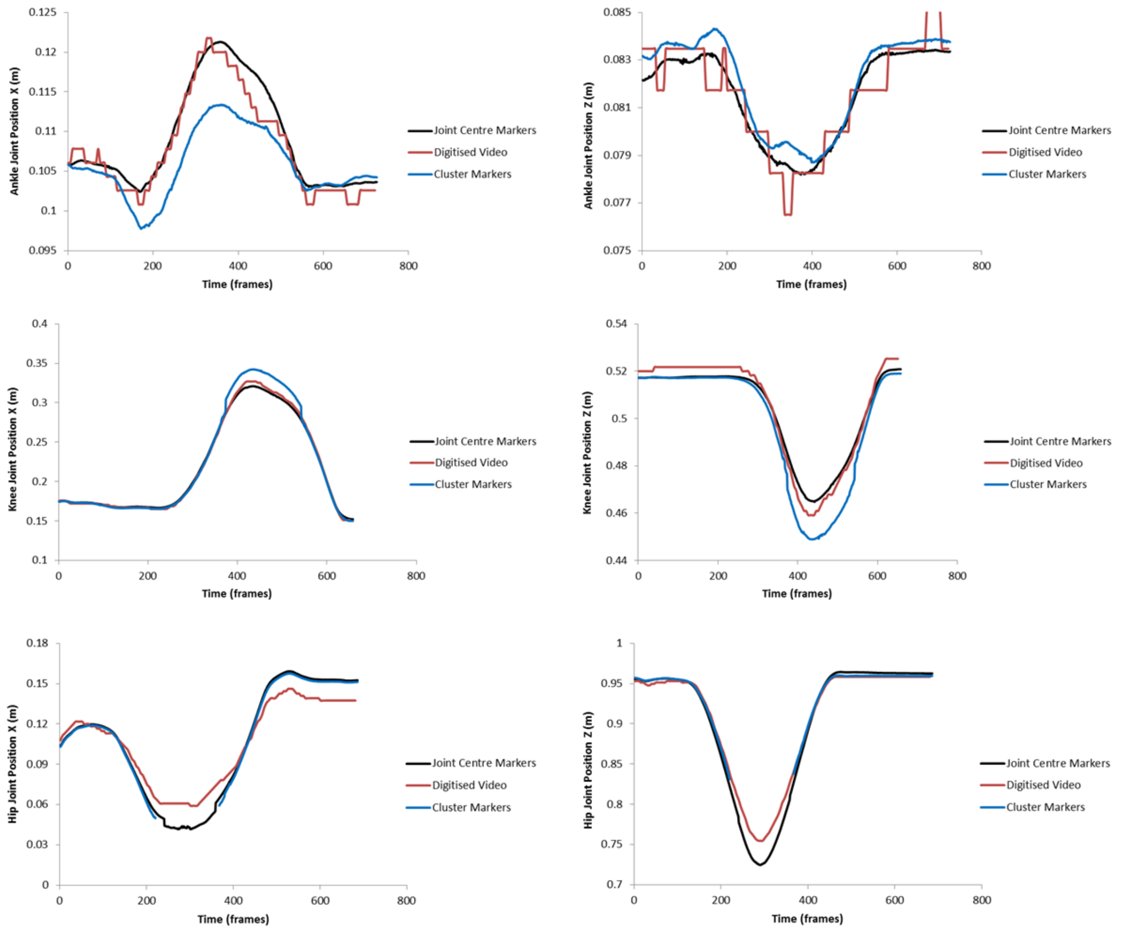


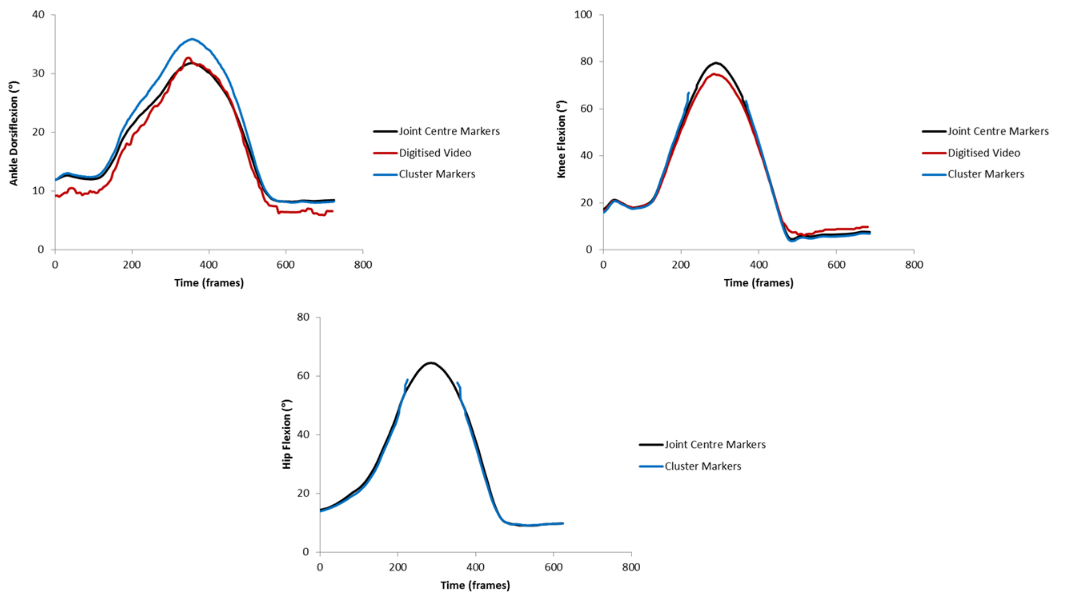
Figure 3.3: Residual error vs. cut-off frequency for determining the optimal cut-off frequency for the medial knee marker position in the squat movement.

Clear differences were found in terms of joint position between the cluster marker data and joint centre marker data (Figure 3.4), and in terms of joint angles (Figure 3.5) at the ankle, knee and hip joint. It is also visible from the graphs (Figure 3.4 and Figure 3.5) and visual representation (Figure 3.2) that the cluster of markers on the thigh disappeared out of view for large portions of the movement due to their position on the back of the leg relative to the position of the cameras high above the subject. Therefore, hip and knee angle is not recorded for a significant proportion of the squat movement. Similar errors were found when measuring differences in hip angle during a lateral leg swing; joint centre markers and digitised video tended to agree while errors of up to 5° were found in hip angle at higher levels of abduction.



Note: video footage was down-sampled to 50 Hz before digitisation; low spatial resolution combined with only small movement of the ankle joint created a stepped position trace.

Figure 3.4: Ankle, knee and hip joint centre positions in the sagittal plane during a squat using joint centre and cluster marker data and high-speed video (250 Hz).



Note: hip angle was not measured using the high-speed video data due to the lack of markers defining the joint centre or pelvis/thorax segments.

Figure 3.5: Angles of flexion/extension of the ankle, knee and hip joint during a squat.

Finally, joint separations were calculated and modelled in Visual 3D. As can be seen from the visual representation (Figure 3.6), maximum joint separations were larger in the cluster method (knee = 33.8 mm, hip = 25.1 mm) than the joint centre marker method (knee = 2.7 mm, hip = 14.4 mm). As Visual 3D uses fixed segment lengths generated from the original static trial, any movement or changes in alignment of the cluster markers due to muscle contraction and skin artefact affects the predicted joint position and generates a separation between segments. This is not so much the case with joint centre markers as there is minimal artefact due to muscle or skin movement, and no changes in alignment, thus making it a more reliable method for this application. Also as cluster markers fall out of view of the Vicon cameras, as occurs at the base of the squat, the prediction of joint centre location becomes less reliable, further reducing the accuracy of a cluster marker approach in this case.

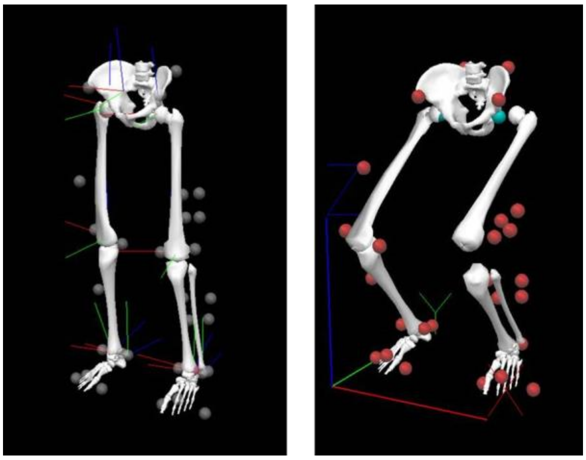


Figure 3.6: Separations at the knee and hip joints due to the cluster method.

3.4.1.2 Markers on Batting Leg Guards

As cluster markers had been deemed unreliable and inaccurate in a cricket batting situation, markers on the batting pads of the subject were trialled as an alternative solution. While the pads have been shown to move relative to the leg in running trials, the movement during a batting movement will be of a lesser magnitude, and motion around the strapped areas at the knee and ankle joints is also found to be lower (Webster & Roberts, 2011).

As such the squat trials used in the analysis of the cluster marker method were repeated, this time having one leg padded with markers placed on the pad parallel with the ankle and knee joints, while the other leg was unpadded and markered with the normal joint centre markers as a comparison (as in Figure 3.8). It was assumed both legs completed the same range of motion during the squat movement. As before, joint angles at the ankle, knee, and hip were compared, this time between padded and unpadded legs (Figure 3.7).

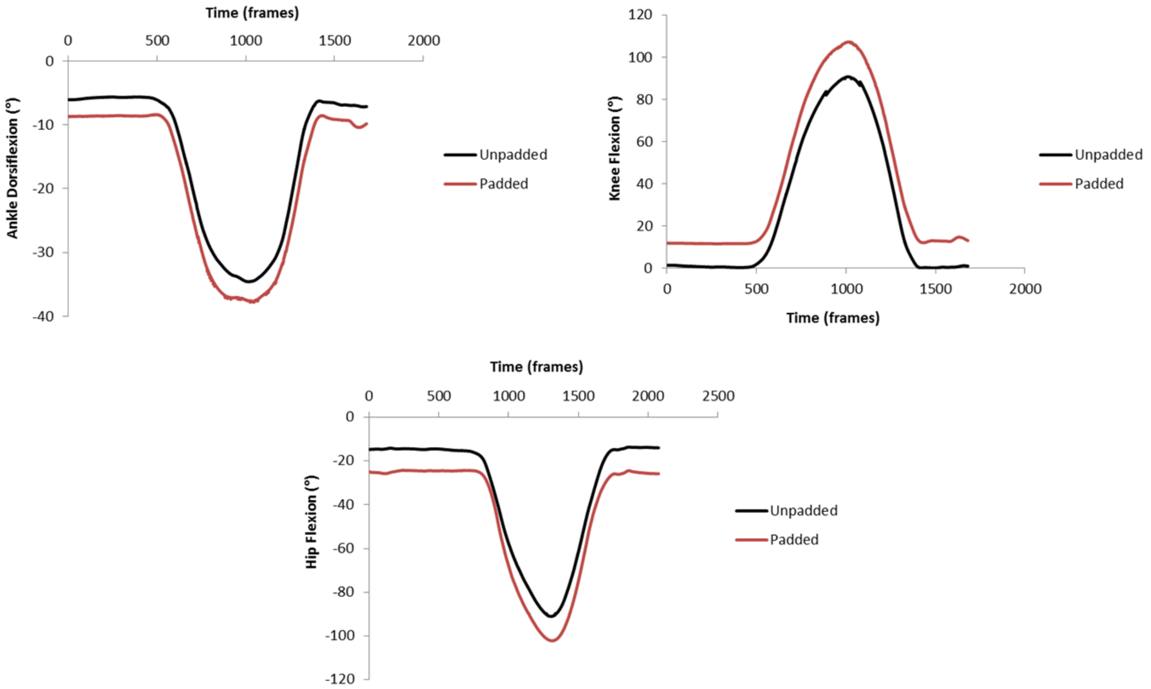


Figure 3.7: Ankle, knee and hip joint angles for padded vs. unpadded legs in a squat.

While there are significant differences between padded and unpadded joint angles for each of the ankle, knee and hip data, the shape of each curve is very similar suggesting a standard offset between padded and unpadded legs. Further analysis of this data, and comparison with digitised video data, showed that the offset between padded and unpadded conditions was fairly similar at all degrees of joint flexion (within 6° for all joints). However, it also showed a trend suggesting areas nearer the top of the squat, i.e. with less flexion (0-50° of knee flexion), had a smaller degree of offset between padded and unpadded legs, whereas areas deeper into the squat, i.e. with more flexion (> 50° of knee flexion), had a larger degree of offset. This was the same across all joints, showing offsets of 1-4° for the ankle, 2-5° for the knee and 3-6° for the hip.

As a result of this fairly consistent offset between padded and unpadded conditions, it was decided that markers placed parallel with the knee and ankle joint on the leg guard itself provided sufficient accuracy to warrant use in future motion capture testing. In order to get as close to the actual joint angles as possible, three static trials were performed on each subject before dynamic testing to determine the specific offset values for their body and pad design. These trials are described in section 3.9 along with the rest of the data capture protocol. The measured offset value was then added to or subtracted from the captured joint angle data as is appropriate for each of the three joints prior to any further analysis being completed.

3.5 Lower Body Marker Set for Static Calibration Trials

For the static calibration trials designed to calculate a standard offset in ankle, knee and hip angles, a marker set of 20 retro-reflective spherical markers was attached to the subject. The subject was asked to put all his lower body protective equipment on apart from his right pad before markers were applied (Figure 3.8). The marker locations are based on examples of Vicon marker sets designed for full body analysis in gait patterns (Vicon, 2012a), golf (Vicon, 2012b) and fast bowling (Ranson et al., 2009), and are given in Table 3.1. Standard 14 mm spherical markers were used throughout, other than on the ASIS locations where larger 25 mm markers were used to minimise them falling out of view due to being covered by the shorts or the torso when bent over during a batting shot.

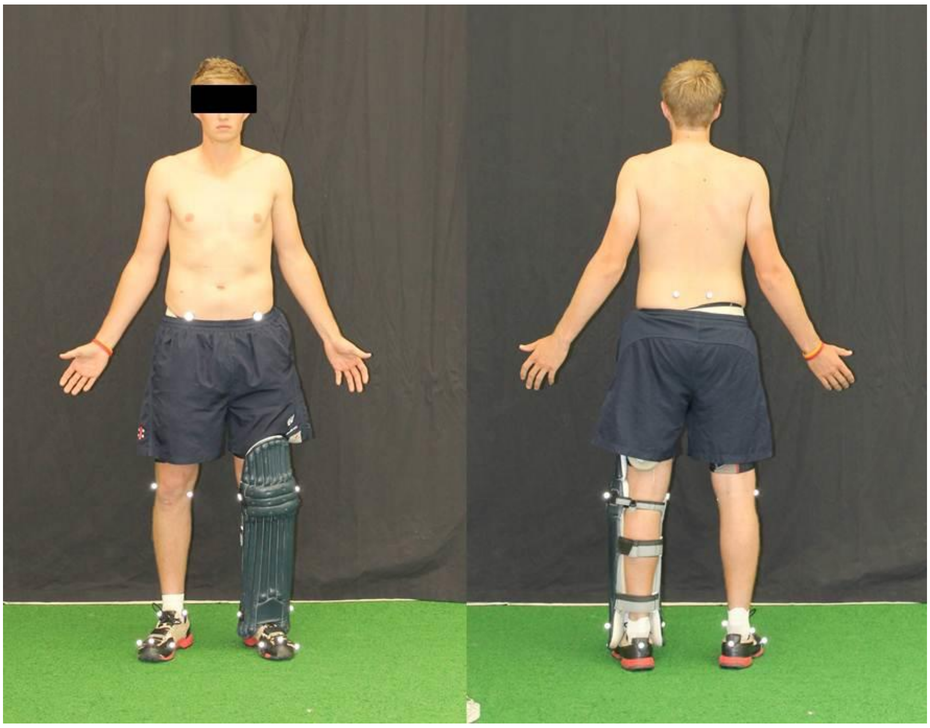


Figure 3.8: Lower body calibration marker set.

Table 3.1: Lower body calibration marker set.

Marker	Definition	Position
LASI	Left anterior superior iliac	Bony protrusion of the left anterior superior iliac
RASI	Right anterior superior iliac	Bony protrusion of the right anterior superior iliac
LPSI	Left posterior superior iliac	Dimple created by the left posterior superior iliac
RPSI	Right posterior superior iliac	Dimple created by the right posterior superior iliac
LKNEM	Left knee medial	Medial side of the left pad parallel with the knee joint
LKNEL	Left knee lateral	Lateral side of the left pad parallel with the knee joint
		The midpoint of the two knee markers defines the knee joint centre
LANKM	Left ankle medial	Medial side of the left pad parallel with the ankle joint
LANKL	Left ankle lateral	Lateral side of the left pad parallel with the ankle joint
		The midpoint of the two ankle markers defines the ankle joint centre
LHEE	Left heel	On the centre line of the left foot at a similar height to the left toe marker
LTOE	Left toe	On the centre line of the left foot approximately at the location of the second metatarsal
LMTPM	Left MTP medial	Medial side of the left MTP joint
LMTPL	Left MTP lateral	Lateral side of the left MTP joint
		The midpoint of the two MTP markers defines the MTP joint centre
RKNEM	Right knee medial	Medial side of the right knee joint
RKNEL	Right knee lateral	Lateral side of the right knee joint
		The midpoint of the two knee markers defines the knee joint centre
RANKM	Right ankle medial	Medial side of the right ankle joint
RANKL	Right ankle lateral	Lateral side of the right ankle joint
		The midpoint of the two ankle markers defines the ankle joint centre
RHEE	Right heel	On the centre line of the right foot at a similar height to the left toe marker
RTOE	Right toe	On the centre line of the right foot approximately at the location of the second metatarsal
RMTPM	Right MTP medial	Medial side of the right MTP joint
RMTPL	Right MTP lateral	Lateral side of the right MTP joint
		The midpoint of the two MTP markers defines the MTP joint centre

3.6 Full Body Marker Set for Dynamic Trials

For the full body marker set the subject was asked to put on all the protective equipment they intended to wear during the dynamic trials. A marker set of 46 retro-reflective spherical markers was attached to the subject and his protective equipment (Figure 3.9). A further 5 spherical markers were attached to the bat, 6 placed on the stumps, and 5 pieces of retro-reflective tape attached to the ball. The marker locations are again based on examples of Vicon marker sets designed for full boy analysis in gait patterns (Vicon, 2012a), golf (Vicon, 2012b) and fast bowling (Ranson et al., 2009), and are given in Table 3.2. Standard 14 mm spherical markers were used throughout, other than on the ASIS and wrist joints where larger 25 mm markers were used to minimise them falling out of view due to obstruction by other areas of the body or clothing. It should be noted that markers on the hands were not included in the marker set as they created significant confusion in the labelling process between bat, wrist, and ASIS markers. A rigid link was therefore assumed between hands and bat (Stuelcken et al., 2005; Tsunoda et al., 2004), and the movement of wrist joint would be implied by the movement of the bat relative to the forearms. Head markers were placed on the helmet as close to the intended landmark as possible.

Table 3.2: Full body batting marker set including human, bat, ball and stumps.

Marker	Definition	Position
LFHD	Left front head	On the helmet directly over the left temple
RFHD	Right front head	On the helmet directly over the right temple
LBHD	Left back head	Left back of helmet – level with temple
RBHD	Right back head	Right back of helmet – level with temple
LSHOT	Left shoulder top	On the acromion process on top of the left shoulder
RSHOT	Right shoulder top	On the acromion process on top of the right shoulder
CLAV	Clavicle	At the upper tip of the joint of the two clavicle bones
C7	7th cervical vertebra	7th cervical vertebra at the base of the neck – prominent when the subject bends their head forwards
STRN	Sternum	At the lower top of the sternum
T10	10th thoracic vertebra	10th thoracic vertebra – count up from L1
L1	1st lumbar vertebra	1st lumbar vertebra – count up from L5 (between PSIS)
RBAK	Right back	Centre of the right scapula – exact position not crucial, just for asymmetry
LASI	Left anterior superior iliac	Bony protrusion of the left anterior superior iliac
RASI	Right anterior superior iliac	Bony protrusion of the right anterior superior iliac
LPSI	Left posterior superior iliac	Dimple created by the left posterior superior iliac
RPSI	Right posterior superior iliac	Dimple created by the right posterior superior iliac
LSHOA	Left shoulder anterior	Anterior of left shoulder joint
LSHOP	Left shoulder posterior	Posterior of left shoulder joint

		The midpoint of the posterior and anterior shoulder markers assists in defining the shoulder joint centre
LELBM	Left elbow medial	Medial side of the left elbow joint
LELBL	Left elbow lateral	Lateral side of the left elbow joint
		The midpoint of the two elbow markers defines the elbow joint centre – this should be done with the arm fully straight
LUPA	Left upper arm	On the left upper arm between the shoulder and elbow joints – exact position not crucial
LWRM	Left wrist medial	Little finger side of the left wrist joint
LWRL	Left wrist lateral	Thumb side of the left wrist joint
		The midpoint of the two wrist markers defines the wrist joint centre
RSHOA	Right shoulder anterior	Anterior of right shoulder joint
RSHOP	Right shoulder posterior	Posterior of right shoulder joint
		The midpoint of the posterior and anterior shoulder markers assists in defining the shoulder joint centre
RELBM	Right elbow medial	Medial side of the right elbow joint
RELBL	Right elbow lateral	Lateral side of the right elbow joint
		The midpoint of the two elbow markers defines the elbow joint centre – this should be done with the arm fully straight
RUPA	Right upper arm	On the right upper arm between the shoulder and elbow joints – exact position not crucial
RWRM	Right wrist medial	Little finger side of the right wrist joint
RWRL	Right wrist lateral	Thumb side of the right wrist joint
		The midpoint of the two wrist markers defines the wrist joint centre
BHND	Bat handle	On the very top of the bat handle in the centre
BB1	Back of bat 1	On the top left hand side of the back of the bat blade as you look at it from behind
BB2	Back of bat 2	On the top right hand side of the back of the bat blade as you look at it from behind
BB3	Back of bat 3	On the bottom left hand side of the back of the bat blade as you look at it from behind
BB4	Back of bat 4	On the bottom right hand side of the back of the bat blade as you look at it from behind
		The four BB markers are used with information about the thickness of the blade to define the front plane of the bat
LKNEM	Left knee medial	Medial side of the left pad parallel with the knee joint
LKNEL	Left knee lateral	Lateral side of the left pad parallel with the knee joint
		The midpoint of the two knee markers defines the knee joint centre
LANKM	Left ankle medial	Medial side of the left pad parallel with the ankle joint
LANKL	Left ankle lateral	Lateral side of the left pad parallel with the ankle joint
		The midpoint of the two ankle markers defines the ankle joint centre
LHEE	Left heel	On the centre line of the left foot at a similar height to the left toe marker
LTOE	Left toe	On the centre line of the left foot approximately at the location of the second metatarsal

LMTPM	Left MTP medial	Medial side of the left MTP joint
LMTPL	Left MTP lateral	Lateral side of the left MTP joint
		The midpoint of the two MTP markers defines the MTP joint centre
RKNEM	Right knee medial	Medial side of the right pad parallel with the knee joint
RKNEL	Right knee lateral	Lateral side of the right pad parallel with the knee joint
		The midpoint of the two knee markers defines the knee joint centre
RANKM	Right ankle medial	Medial side of the right pad parallel with the ankle joint
RANKL	Right ankle lateral	Lateral side of the right pad parallel with the ankle joint
		The midpoint of the two ankle markers defines the ankle joint centre
RHEE	Right heel	On the centre line of the right foot at a similar height to the left toe marker
RTOE	Right toe	On the centre line of the right foot approximately at the location of the second metatarsal
RMTPM	Right MTP medial	Medial side of the right MTP joint
RMTPL	Right MTP lateral	Lateral side of the right MTP joint
		The midpoint of the two MTP markers defines the MTP joint centre
ST – BL	Stumps – bottom of leg	At the bottom of leg stump
ST – TL	Stumps – top of leg	At the top of leg stump
ST – BM	Stumps – bottom of middle	At the bottom of middle stump
ST – TM	Stumps – top of middle	At the top of middle stump
ST – BO	Stumps – bottom of off	At the bottom of off stump
ST – TO	Stumps – top of off	At the top of off stump
BALL1	Ball marker 1	On the circumference of the leather part of the ball
BALL2	Ball marker 2	On the circumference of the leather part of the ball
BALL3	Ball marker 3	On the circumference of the leather part of the ball
BALL4	Ball marker 4	On the circumference of the leather part of the ball

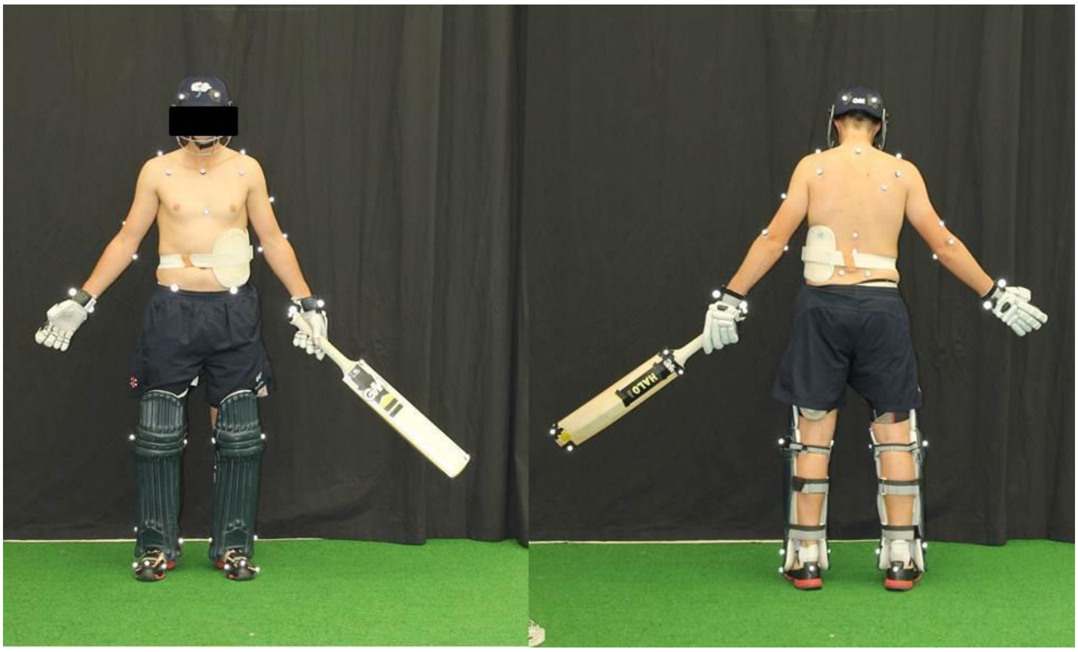


Figure 3.9: Full body marker set.

3.7 Experimental Setup

Each data collection took place in the National Cricket Performance Centre (NCPC) at Loughborough University. This is a purpose built cricket centre equipped with retractable net lanes and a realistic floor surface, so is the perfect environment for data capture. The third lane of six was used such that there was sufficient space either side for equipment setup and preparation of following subjects. Four separate data capture sessions were carried out; one in 2012, one in 2013 and two in 2014. Each session used largely the same equipment setup, with only minor changes being made throughout to increase the efficiency and speed of data capture.

Eighteen MX Vicon cameras (Vicon Motion Systems, Oxford, UK) were positioned around the batting area in order to fully capture the area in which the movement was performed (Figure 3.10 and Figure 3.11). These cameras were all placed on tripods at a height of approximately 4 m, at varying distances from the batsman based on the angle from which they were viewing the movement and the type of lens attached to each. Motion data was captured at 250 Hz in order to easily synchronise with the high-speed video, with a sufficiently large capture area to track the human and some aspects of ball motion around the batsman (approximately 7x3x3 m). The centre of the batting area was defined by a force plate, upon which all subjects would be instructed to take up their stance before each batting shot.

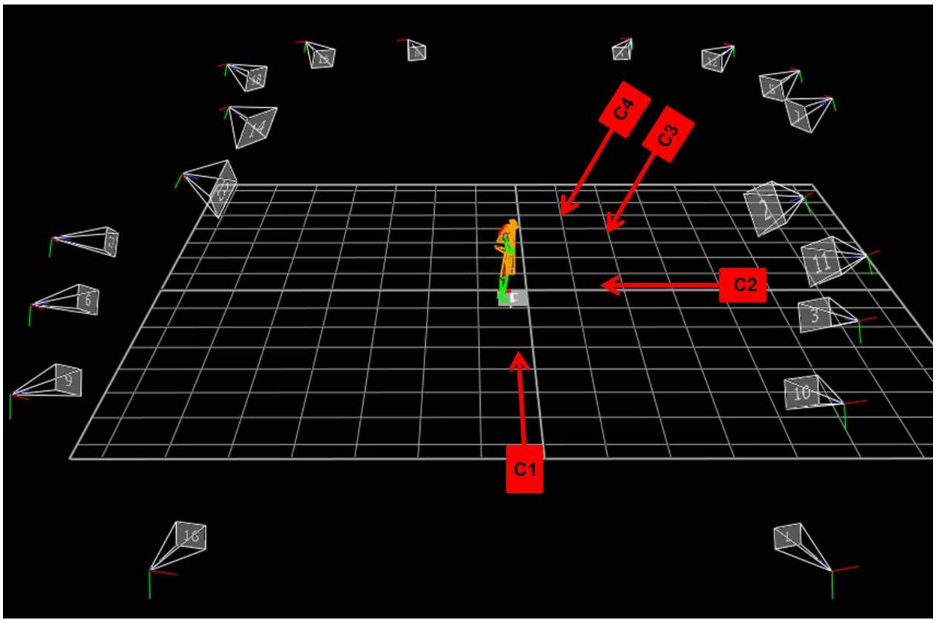


Figure 3.10: Experimental setup for a batting trial; the subject in the centre of the capture volume on the force plate, and the position of the 18 Vicon (1 – 18) and 4 high-speed video cameras (C1 – C4).

Four high-speed video cameras were also positioned around the subject; two to film the batsmen themselves (one on the ground directly in front of the batsman [C1], and one parallel to the batsman at 90° to the pitch [C2]), and two to track the progress of the ball from release, through bounce to impact (both at an angle behind the batsman such that ball release, bounce and impact were all in view [C3&C4]) (Figure 3.10). Each camera was setup to capture at 250 frames per second and synchronised to start at the same time as the Vicon system. After the first data capture session in 2012, the cameras filming the batsman were removed, and three cameras used in turn to film the progress of the ball in order to improve the speed and efficiency of data capture. A Trackman ball flight analysis device relying on radar technology was also used to capture ball release speed from the bowling machine, Sidearm, and bowler deliveries.

Figure 3.11: Equipment setup at the NCPC for the batting trials.

3.8 Subjects

In total 31 male batsmen were recruited for this study (Table 3.3). 23 of the subjects were provided by the ECB from their elite and development playing squads, while the remaining eight were club players from the local area. At the time of testing subjects included two batsmen with full international playing honours, six from the England Lions squad, twelve that had represented both county sides and the England under 19's, and three solely county level players. Of the eight club players, five were premiership standard batsmen, and the remaining three were lower league players. Although this group represents a large spread of abilities, amateur players were required to answer one of the primary research questions, and for logistical reasons elite players were unavailable at some of the testing sessions.

Not all subjects completed the entire testing protocol, either due to time constraints or a lack of the appropriate personnel to deliver the Sidearm or act as a bowler. Two of the elite batsmen also participated in the testing twice, in each case completing different sections of the testing protocol. All subjects completed health screen questionnaires and gave informed consent in accordance with the university's ethical advisory committee procedures prior to testing (Appendix 1).

Table 3.3: Subjects participating in the study.

Subject No.	Playing Level	Age	Height (m)	Mass (kg)
1	U19/County	20	1.806	79.9
2	U19/County	19	1.809	79.1
3	Lions	25	1.820	74
4	Lions	22	1.833	94.3
5	U19/County	22	1.823	86.2
6	U19/County	17	1.710	69.0
7	Lions	19	1.886	86.8
8	U19/County	18	1.811	72.8
9	England	21	1.826	80.3
10	Lions	22	1.820	94.9
11	U19/County	21	1.812	76.1
12	Lions	20	1.887	83.2
13	England	28	1.750	82.7
14	Lions	20	1.913	97.8
15	County	25	1.835	87.9
16	U19/County	21	1.838	80.4
17	U19/County	18	1.757	76.1
18	Club	21	1.803	72.7
19	Club	23	1.770	70.1
20	Club	25	1.792	72.9
21	Club	25	1.802	89.5
22	Club	26	1.792	78.0
23	Club	24	1.865	82.4
24	Club	26	1.811	74.8
25	Club	25	1.875	93.2
26	County	24	1.830	76.5
27	U19/County	19	1.772	80.1
28	County	22	1.872	82.7
29	U19/County	23	1.815	78.2
30	U19/County	18	1.794	75.9
31	U19/County	17	1.828	65.8
	Mean	21.8	1.818	80.5
	St. Dev.	3.0	0.045	7.9

Note: England = full international playing honours, Lions = England Lions squad, County = any of the 18 current first class county squads, U19 = England under 19's squad, Club = premiership club squad.

3.9 Motion Data Collection Procedure

3.9.1 Static Trials

Before any dynamic trials could be completed, a series of static trials were carried out to determine the joint angle offsets between a padded and unpadded leg. Initially the subject was markered with the lower body marker set described earlier, and completed three static trials with different degrees of hip, knee and ankle flexion. This involved one standing trial, and two seated on a stool with the knees bent at approximately 30° and 60° respectively (Figure 3.12) to calculate the angular offset at the ankle, knee and hip joints. Mean offsets for flexion/extension were 2.9 ± 4.1° at the ankle, 3.6 ± 4.8° at the knee, and -4.4 ± 2.7° at the hip joint (individual subject results can be found in Appendix 2). Substantial variability was seen between individual offsets, which were likely attributable to the different designs of leg pads used by each batsman. These offsets were then subtracted from the calculated joint angles during the dynamic trials in order to gain a more accurate measurement of ankle, knee, and hip angles.

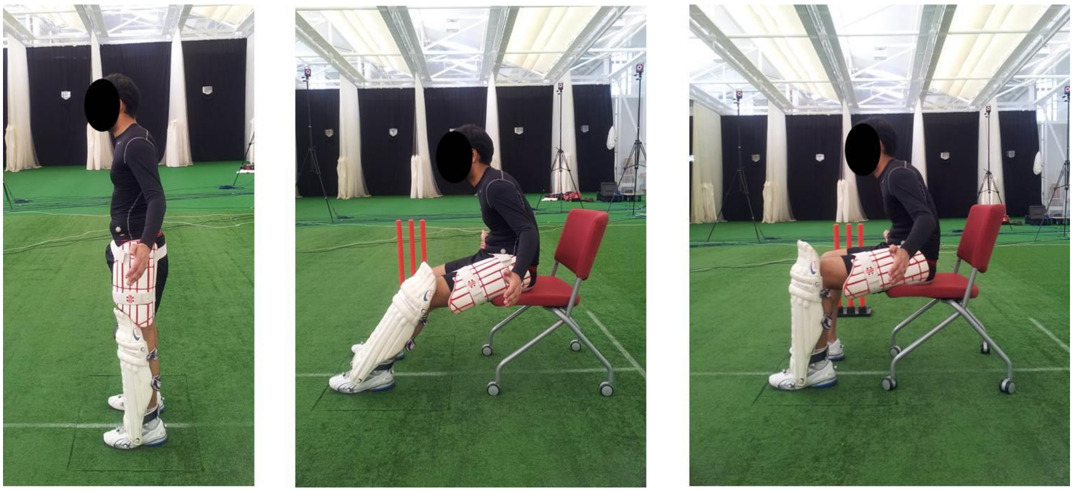


Figure 3.12: Lower body static subject calibration trials.

Once this was complete, the subject put the rest of their batting equipment on and was markered up using the full body marker set. They were then asked to complete one additional static trial in the anatomical position (Figure 3.9) ensuring they were holding the bat, and both the stumps and ball were in view. It was essential that all markers were clearly in view during this trial, as this would be used to create and define the biomechanical model used to analyse all future dynamic trials.

3.9.2 Dynamic Trials

Two common batting shots were chosen for primary analysis with the help of the England and Wales Cricket Board (ECB) batting coaches; these were the forward drive and pull shot. These were chosen as both are common attacking shots that are significantly different from each other. The forward drive is played by stepping forwards with a vertical bat to a ball of full length, with the aim of striking through the line of the ball along the ground past the bowler (Figure 3.13). The pull or hook shot however is played by stepping back with a horizontal bat to a ball short of a length, with the aim of striking across the line of the ball through the leg-side (Figure 3.14 and Figure 3.15) (ECB, 2009). The choice of which technique to apply when facing a short pitched ball depends on the preferences of the batsman, speed of bowling and height of the approaching delivery.

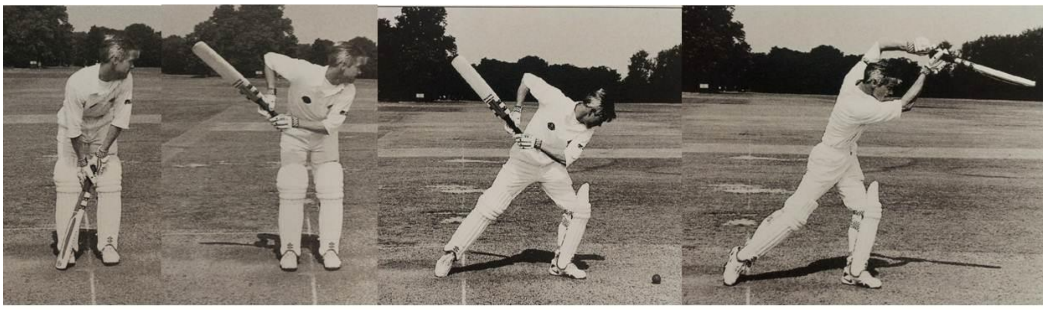


Figure 3.13: The forward drive (adapted from www.cricketcoachmaster.co.uk).

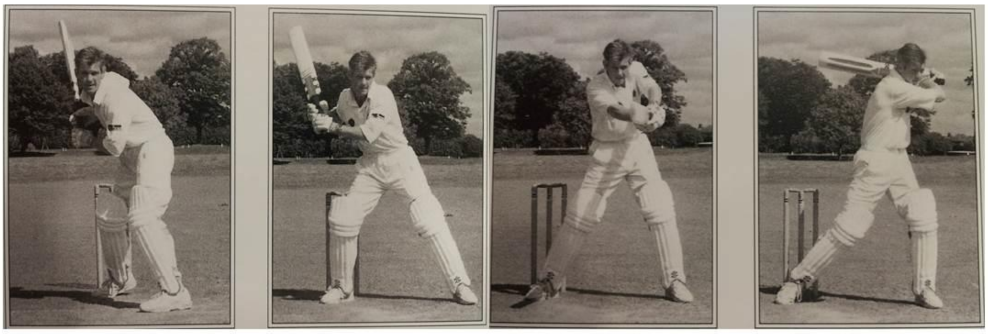


Figure 3.14: The pull shot technique (adapted from www.cricketcoachmaster.co.uk).

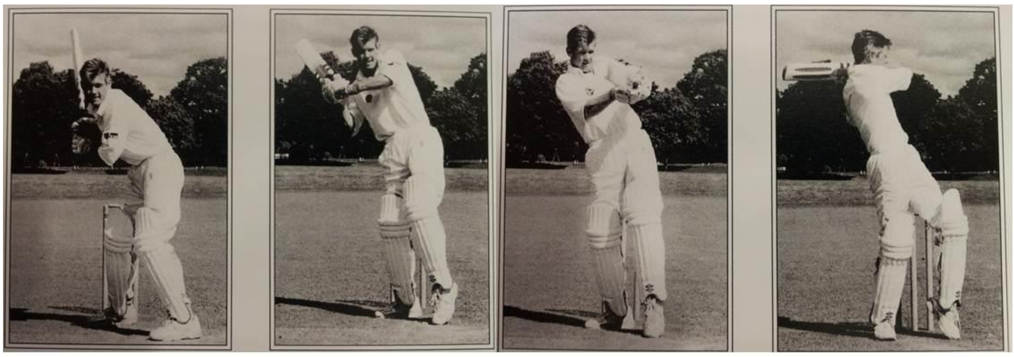


Figure 3.15: The hook shot technique (adapted from www.cricketcoachmaster.co.uk).

The full hitting protocol consisted of five unique stages which are described below. As previously mentioned not all subjects completed the full protocol due to time or personnel constraints. In order to show which subjects completed which trials a table has been included at the end of this section showing the number of successful trials completed by all subjects in each stage of the testing protocol (Table 3.4).

3.9.2.1 Static Ball Trials

The first stage of the protocol involved subjects completing twelve forward drives and twelve pull shots simply hitting a ball placed on a tee at a suitable height and distance away as determined by the batsman. Subjects were instructed to make their movements and shot execution as realistic as possible to a match situation against a live bowler, hitting the forward drive straight past the bowler along the ground, and the pull shot in front of square on the leg-side again along the ground, both at match realistic speed.

3.9.2.2 Bowling Machine Trials

For the second stage of the hitting protocol subjects then completed the same exercise of hitting twelve drives and pulls this time against deliveries from a bowling machine. Subjects were given several warm up trials in order to become accustomed to the pace and bounce of the delivery, and to ensure the ball was pitching in approximately the right position for the shot. The high repeatability of the bowling machine allowed the ball to be delivered into approximately the same area for each trial, thus allowing the subject to repeat the same shot one delivery after the next. Additional trials were completed where possible to ensure every subject had played at least eight successful forward drives and pull shots. Due to problems with the reflective tape, motion capture data of the ball was not recorded for the bowling machine trials during the first data capture session (subjects 1 to 11).

3.9.2.3 Range Hitting Trials

Having completed the forward drives and pull shots against the bowling machine, subjects were asked to complete ten to fifteen trials hitting forward drives over the bowler's head aiming to hit a straight six. As above these trials were delivered by the bowling machine, and subjects were entitled to a number of warm up deliveries in order to become accustomed to the pace and pitch location of the bowling machine. Additional trials were again completed where possible to ensure each subject had played at least eight or more successful shots.

3.9.2.4 Sidearm Trials

The next set of trials involved the use of a coaching aid known as a 'Sidearm' (www.Sidearm-cricket.com) (Figure 3.16). This is a tool designed to help coaches deliver cricket balls at high speed without as much effort or stress being placed on the shoulder, and with more realistic visual cues and trajectories being produced than when using a bowling machine.

Subjects faced two sets of deliveries from the Sidearm delivered by one of two highly experienced international coaches and Sidearm users; those where they knew the intended ball bounce location and shot they should play (ten drives and ten pulls), and those where they didn't know the bounce location thus had a choice of either the forward drive or the pull shot (twenty trials in total, ten intended to be driven and ten to be pulled). Clearly there is more variability in the delivery method and therefore accuracy of the Sidearm compared to the bowling machine, and the shot selection aspect of this set of trials provides less shot repeatability; this is reflected in the number of successful trials where a forward drive or pull shot was played, which was less than when facing the bowling machine. Additional trials to ensure each subject played more shots of each type were not completed due to time constraints and to avoid over-stressing the shoulder of the coach.

Figure 3.16: Sidearm Pro ball thrower (adapted from www.Sidearm-cricket.com).

3.9.2.5 Bowler Trials

Finally, subjects faced a series of twenty deliveries from a bowler. All bowlers gave informed consent to take part in the study, and were fast bowlers of a similar standard to the batting subjects. The bowlers were instructed for each delivery whether to bowl a short ball suitable to pull or a full ball suitable to drive; of the twenty trials it was intended ten would produce a pull shot and ten a forward drive. However, as with the Sidearm trials the repeatability of the bowler is low, thus a low percentage of deliveries bounced in the correct location to allow the specified shot. Again no additional trials were performed to allow each batsman to perform more shots of each type due to time constraints and to avoid the bowler delivering too many balls that he may become over-fatigued or risk injury. Examples of one subject playing a forward drive and a pull shot from the high-speed video are shown in Figure 3.17 and Figure 3.18.

Figure 3.17: Example of a forward drive from the testing session.

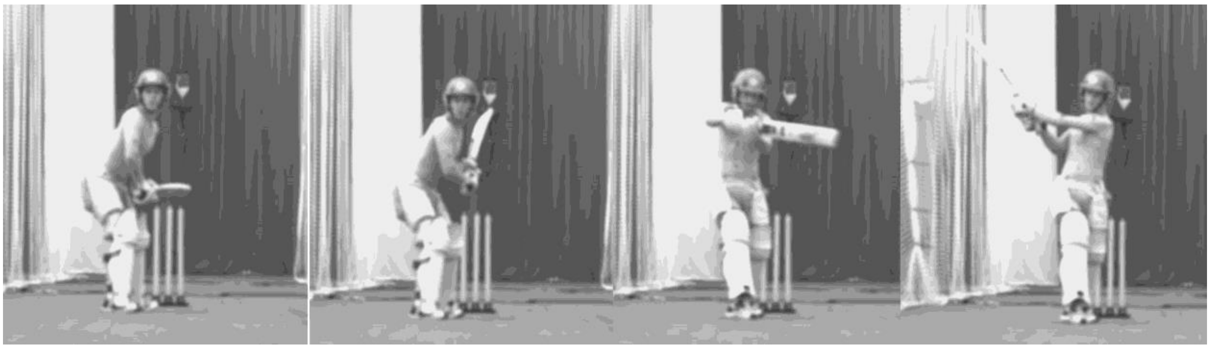


Figure 3.18: Example of a pull shot from the testing session.

3.10 Measurement of Bat Characteristics

A series of measurements were also taken of each player's bat, for use in later performance analyses and kinematic assessments. These measures were not included in the first data capture session, thus only 20 of the 31 players' bats were assessed. Initially the bat's mass and a variety of dimensional measurements were taken (Figure 3.19). A rig was then designed that allowed the measurement of the position of the centre of mass in both the vertical (Figure 3.20) and anterior-posterior planes of the bat (Figure 3.21), relying on the balancing point and suspension of the bat under gravity respectively. These would allow the creation of a virtual bat centre of mass position during dynamic trials, and the output of various features of bat and ball movement relative to that point. Detailed results of each subject's bat characteristics are available in Appendix 2.

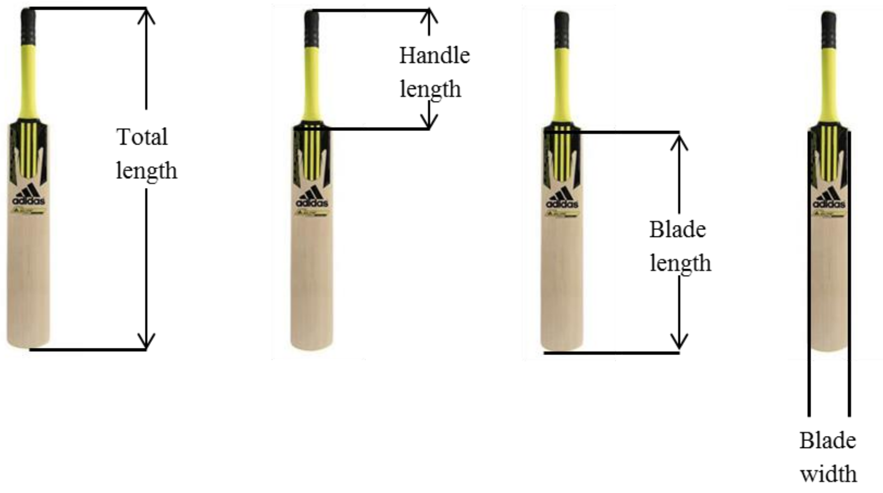


Figure 3.19: Dimensional measurements taken of the cricket bat (adapted from www.cricketdirect.co.uk).

Figure 3.20: Centre of mass measurement of a cricket bat in the vertical plane.

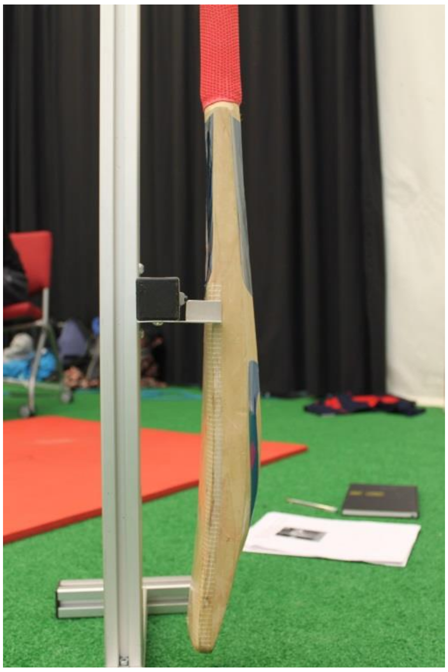


Figure 3.21: Centre of mass measurement of a cricket bat in the anterior-posterior plane.

3.11 Chapter Summary

This chapter has provided the details of the testing procedures used to capture the required kinematic data in the four major data collection sessions. It has outlined the marker sets and experimental protocols used for both static and dynamic trials, and the participants involved in each section of testing. Finally, it has described additional anthropometric and bat measurement data acquired during the data collection sessions.

Table 3.4: Successful trial count for all subjects in each stage of the testing protocol (numbers in brackets represent the number of range hitting trials where the ball was impacted in a forward direction).

SUB NO.	YEAR	DISCIPLINE	LEVEL	AGE	HEIGHT (m)	MASS (kg)	Static Ball		Bowling Machine		Power Hitting	Sidearm Known		Sidearm Unknown		Bowler	
							Drive	Pull	Drive	Pull	Drive	Drive	Pull	Drive	Pull	Drive	Pull
1	2012	LH	U19/C	20	1.806	79.9	11	11	9	10	-	2	6	2	3	3	2
2	2012	LH	U19/C	19	1.809	79.1	12	4	8	9	-	5	4	4	2	4	1
3	2012	LH	LIONS	25	1.820	74.0	6	8	9	11	-	7	8	4	3	-	-
4	2012	RH	LIONS	22	1.833	94.3	11	7	9	12	-	3	8	3	3	4	3
5	2012	RH	U19/C	22	1.823	86.2	12	12	9	9	-	4	6	5	4	3	-
6	2012	LH	U19/C	17	1.710	69.0	10	5	10	-	-	3	5	4	2	3	3
7	2012	RH	LIONS	19	1.886	86.8	2	7	11	11	-	4	9	6	2	3	3
8	2012	RH	U19/C	18	1.811	72.8	9	10	11	12	-	4	8	2	3	2	2
9	2012	RH	ENG	21	1.826	80.3	11	10	10	12	-	3	9	3	4	5	4
10	2012	LH	LIONS	22	1.820	94.9	9	12	12	9	-	2	7	5	3	3	4
11	2012	RH	U19/C	21	1.812	76.1	10	6	10	10	-	4	6	5	6	3	1
12	2013	RH	LIONS	20	1.887	83.2	-	-	-	-	20 (13)	-	-	-	-	-	-
13	2013	RH	ENG	28	1.750	82.7	-	-	-	-	20 (16)	-	-	-	-	-	-
14	2013	LH	LIONS	20	1.913	97.8	10	8	7	8	14 (12)	3	4	2	3	4	1
15	2013	RH	C	25	1.835	87.9	10	10	8	6	9 (9)	3	4	5	2	3	2
16	2013	LH	U19/C	21	1.838	80.4	10	10	8	7	15 (14)	4	5	4	3	3	4
17	2013	RH	U19/C	18	1.757	76.1	9	10	8	8	12 (11)	3	5	3	2	-	3
18	2014	RH	CLUB	21	1.803	72.7	8	8	9	10	13 (10)	-	-	-	-	-	-
19	2014	LH	CLUB	23	1.770	70.1	9	10	11	10	20 (17)	-	-	-	-	-	-
20	2014	RH	CLUB	25	1.792	72.9	10	10	8	10	10 (10)	4	4	3	3	4	4
21	2014	RH	CLUB	25	1.802	89.5	10	10	12	10	13 (11)	3	4	-	4	3	4
22	2014	LH	CLUB	26	1.792	78.0	9	5	9	11	14 (13)	3	5	2	2	3	3
23	2014	RH	CLUB	24	1.865	82.4	10	10	11	10	17 (12)	3	5	4	4	5	4
24	2014	RH	CLUB	26	1.811	74.8	8	7	11	-	18 (16)	-	-	-	-	-	-
25	2014	RH	CLUB	25	1.875	93.2	10	7	10	10	14 (11)	-	-	-	-	-	-
26	2014	RH	C	24	1.830	76.5	10	10	10	10	13 (13)	-	-	-	-	-	-
27	2014	RH	U19/C	19	1.772	80.1	11	9	8	11	16 (12)	-	-	-	-	-	-
28	2014	RH	C	22	1.872	82.7	10	10	9	10	10 (9)	-	-	-	-	-	-
29	2014	RH	U19/C	23	1.815	78.2	10	10	9	9	12 (12)	-	-	-	-	-	-
30	2014	LH	U19/C	18	1.794	75.9	10	10	11	8	8 (8)	-	-	-	-	-	-
31	2014	RH	U19/C	17	1.828	65.8	9	9	9	11	11 (10)	-	-	-	-	-	-
			AV	**21.8**	**1.8**	**80.5**	**9.5**	**8.8**	**9.5**	**9.8**	**14.0 (12.0)**	**3.5**	**5.9**	**3.7**	**3.1**	**3.4**	**2.8**
			ST DEV	3.0	0.0	7.9	1.9	2.1	1.3	1.5	3.6 (2.4)	1.1	1.8	1.2	1.0	0.8	1.1

SUM	**LH**	96	83	94	83	71 (64)	29	44	27	21	23	18
	RH	180	172	182	181	208 (175)	38	68	39	37	35	30
	TOTAL	276	255	276	264	279 (239)	67	112	66	58	58	48

CHAPTER 4

METHODS 2 – DATA PROCESSING

4.1 Chapter Outline

This chapter describes the use of data processing in this study, including details of the 3D motion capture system used and its calibration, a definition of the model and body segments applied to the kinematic data, and an overview of the post-processing methods employed.

4.2 Acquisition of Movement Data

The Vicon 3D motion capture system selected for this project uses passive retro-reflective markers attached to key body landmarks and joint centres in order to track subject motion. Each MX camera (Figure 4.1) consists of a video camera, a strobe assembly consisting of a ring of infrared light emitting diodes (LEDs), a lens and an optical filter. The infrared light emitted by the cameras is reflected by the body markers and is captured by the cameras.

Figure 4.1: Vicon MX camera (adapted from www.cgsociety.org).

4.2.1 Camera Calibration

Before any motion data was captured, the Vicon system underwent two calibration steps. Firstly, the system was taken through a dynamic calibration in order to gain a measure of accuracy or error in the current setup. This involved waving a calibration 'wand' with known spacing between markers around the desired capture volume. For this study a 390 mm wand fitted with three 25 mm diameter spherical markers was chosen. The Vicon system in this case recorded 4000 frames of motion, and using the known spacing between markers calculated the image error (residual error in pixels) present in each camera. If the calibration error results were unacceptable (in this case unacceptable was deemed to be having values > 0.3), the position and settings of each camera were adjusted and the calibration procedure was repeated. The image errors produced for each camera on the first and second day of testing in 2012 are shown in Table 4.1 as an example of the values achieved throughout all testing sessions.

Table 4.1: Vicon camera calibration values for the first data collection session.

Camera	Day 1 Image Error	Day 2 Image Error
1	0.2441	0.2034
2	0.2639	0.2122
3	0.2217	0.1847
4	0.2166	0.2068
5	0.2804	0.2451
6	0.2175	0.1959
7	0.2533	0.2274
8	0.1910	0.1599
9	0.2028	0.2065
10	0.2347	0.2104
11	0.2090	0.1813
12	0.2948	0.2841
13	0.2915	0.2644
14	0.2140	0.1867
15	0.2352	0.2010
16	0.2516	0.2163
17	0.2797	0.2318
18	0.2241	0.1995
Mean error (std. dev.)	0.2414 (0.0338)	0.2125 (0.0301)
Error range (high–low)	0.1038 (0.2948-0.1910)	0.1242 (0.2841-0.1599)

4.2.2 Determining Marker Spatial Reconstruction Accuracy

While these image errors give a guide to system performance over time, and are particularly useful for identifying a particular camera that may be out of focus or zoomed in on the wrong area of the capture volume, they are somewhat arbitrary values that don't take into account any of the specifics of the setup or system in use. What is of more interest is the spatial accuracy of the 3D reconstruction. The Vicon system is MDD (Medical Devices Directive) certified as having an accuracy of < 1 mm in 3D reconstruction of an individual marker location in a capture volume of 3x3x3 m, however this is highly dependent on camera optimisation, capture volume and environmental factors (Tsui, F. 2012, personal communication – Vicon Support, 7 July). The accuracy of a specific setup can be measured in two ways; either by calculating the 'residual' values of each camera or by passing an array of markers with known separation through the capture volume, and measuring the recorded distance between them.

In this case the second option of passing a set of markers with known spacing through the calibration space was selected. Firstly, this takes less time, but also because the residual value of a camera is dependent on a number of factors such as the pixel arrangement of the camera, the lens type, the distance to the capture volume, the recorded movement of the calibration wand, and the camera settings, it is somewhat less valid in comparison between different cameras in the setup (Tsui, F. 2012, personal communication – Vicon Support, 7 July).

Initially the reconstructed distance between three pairs of static markers placed on the stumps was assessed across 3 trials from each testing session. Standard deviations from the mean separation ranged from 0.16 – 0.24 mm, with a maximum recorded deviation from the mean of 1.03 mm. When considering marker separations of 180-710 mm, as in this case, the maximum recorded error is less than 0.6% of the actual measurement, suggesting a high level of accuracy in recording the position of static markers.

The same three marker wand as was used in calibration was passed through the capture volume with random orientations and speeds on each day of testing in order to assess the spatial reconstruction accuracy of the system when tracking dynamic markers. The distance between the three pairs of markers on the wand was then measured in each case (Figure 4.2). Standard deviations from the mean separation ranged from 0.5-1.2 mm, with a maximum deviation of 3.0 mm. In this case, considering marker separations of 130-390 mm, the maximum recorded error accounts for 2.3% of the actual measurement, while the maximum recorded standard deviation from the mean accounts for less than 1% of the measured separation. While these error values are higher than in the static marker case, the values are still low, indicating a relatively high level of accuracy in tracking dynamic markers, and thus giving confidence to any conclusions drawn as a result of the marker position data.

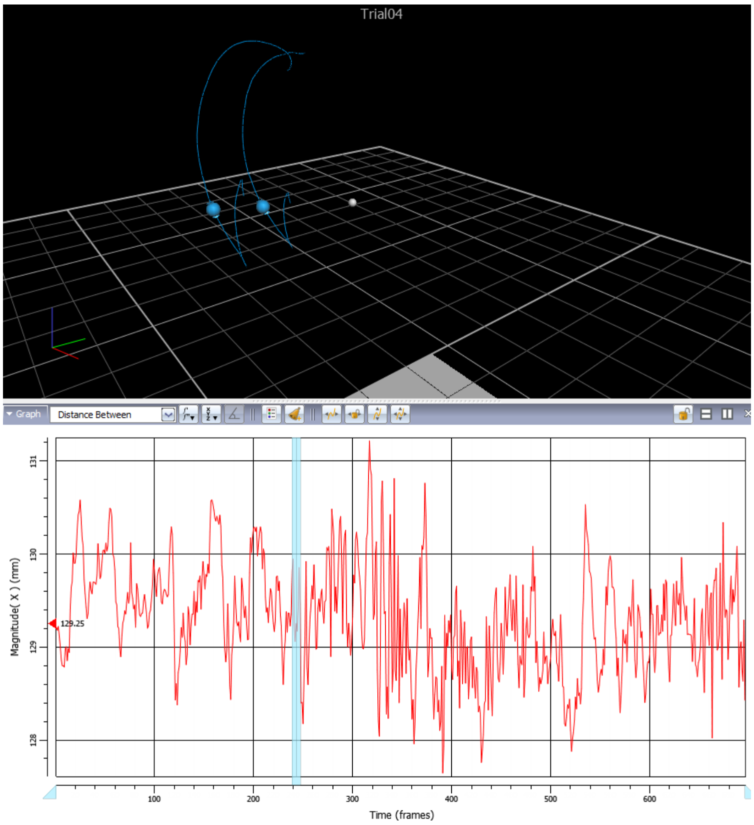


Figure 4.2: Marker separation during calibration trial.

Although a high level of marker spatial reconstruction accuracy had been achieved when tracking the motion of the calibration wand through the capture volume, particular care must be taken when tracking the motion of the bat and ball. Given the high movement speed of both during the batting action particularly around the time of impact, the increased possibility of marker occlusion behind the body, and the use of reflective tape as markers on the ball as opposed to the spherical markers used elsewhere, additional checks are required to validate the accuracy of their tracking.

Initially the level of marker occlusion experienced when tracking the four bat blade markers was assessed for two forward drives and two pull shots. The total number of cameras able to see each bat marker was recorded for each frame of the trial (Figure 4.3). Increased occlusion was found during the downswing and around the time of impact, particularly when considering the top marker nearest to the body (BB1 for right handed batsmen, BB2 for left handed batsmen). Lower levels of occlusion were found for the two markers placed at the bottom of the bat (BB3 and BB4), with the total number of cameras able to see each marker not dropping below four for any shot.

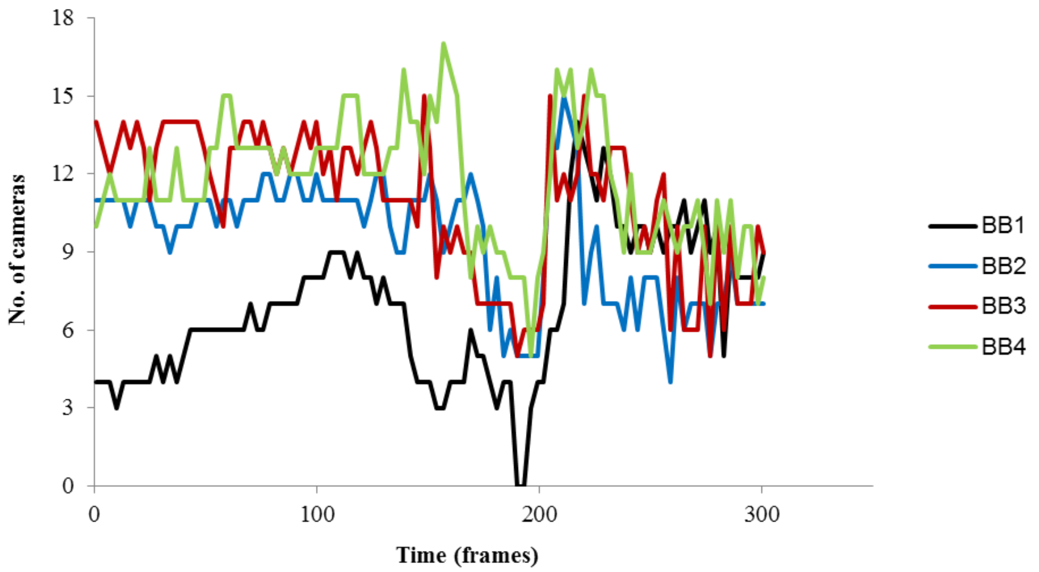


Figure 4.3: Bat marker occlusion in an example pull shot by a right handed batsman.

The reconstruction accuracy of the system when tracking these markers was then assessed as before, by measuring the distance between marker pairs this time on the bat face, for 293 forward drives, 62 range hitting trials, and 306 pull shots. Standard deviations from the mean separation were highest for the pair of markers at the top of the bat face (BB1 – BB2; 3.4 to 4.9 mm), and lowest for the pair of markers at the bottom of the bat (BB3 – BB4; 0.7 to 1.2 mm). As expected the largest measured deviations from the mean separation were found around and just after the time of impact, where the bat markers are likely to experience high levels of acceleration as a result of the bat's collision with the ball. The lower levels of occlusion and higher spatial reconstruction accuracy found for the markers at the bottom of the bat (BB3 and BB4) confirm these are the best markers to use for any calculations of bat position or angle, while the high levels of occlusion and poor spatial reconstruction accuracy found in the marker positioned at the top of the bat blade nearest the body (BB1 or BB2) suggest use of this marker for later analysis should be kept to a minimum. The ball tracking ability of the system was qualitatively checked after each calibration, to ensure that markers on the ball were clearly visible on the reconstruction throughout the desired capture volume. Reflective tape on the balls was also replaced after each subject's hitting trials, in order to minimise the effects of wear and maintain high levels of visibility in future reconstructions.

4.2.3 Defining the Origin and Lab Coordinate System

The second stage of calibration involved capturing a static trial of a four 14 mm marker Ergocal calibration frame. This was placed such that it sat level with the pitch surface on the back left hand corner of the force plate; this calibrates the space ensuring the X, Y and Z axes are aligned in the desired directions relative to the pitch (Figure 4.4), and that the software knows where each camera is relative to the calibrated origin. Once the system had been calibrated and the origin and axes defined, the capture of dynamic batting trials could start.

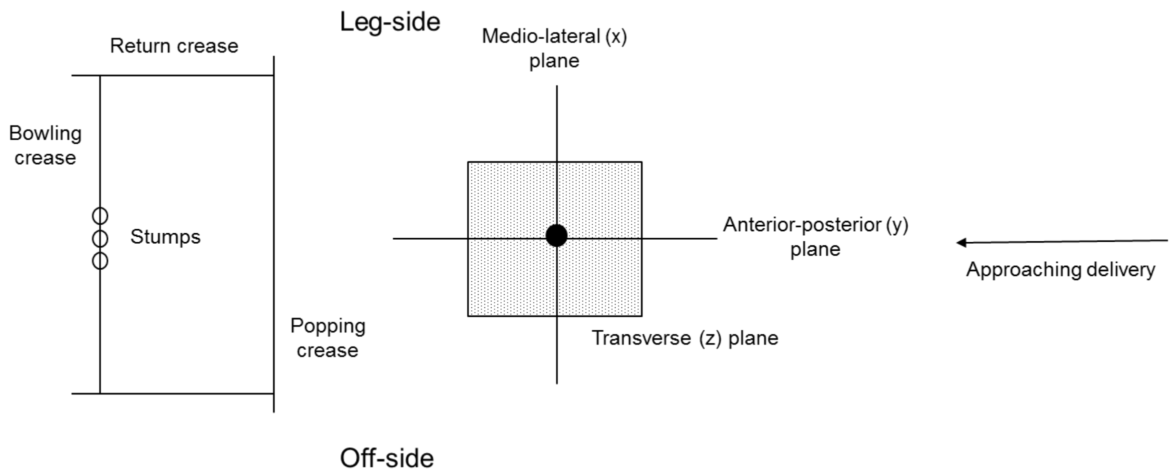


Figure 4.4: Global coordinate system, axes, and planes.

4.3 Preparation of Movement Data

4.3.1 Reconstructing Marker Locations

Following the capture of dynamic trials, marker locations in time and space were reconstructed on Vicon Nexus software (Vicon Motion Systems, Oxford, UK) for each batting trial. Nexus uses 2D information from each camera to form a 3D reconstruction of the position of each individual marker. If two or more cameras can see the position of an individual marker it is recognised and its position can be calculated using triangulation algorithms. Settings yielding the best quality reconstruction (i.e. less flickering and more thorough labelling) were chosen for use.

4.3.2 Labelling of Dynamic Trials

Having reconstructed the 3D movement data, markers were labelled using Vicon Nexus software. Initially the static trial was labelled for each subject; two different static trials were tested, one with the batsman in an anatomical position and another with the batsman in his stance (Figure 4.5). Labelling results were subjectively found to be more complete when using the static trial with the batsman in his stance, so this was used for future labelling tasks. This static trial was then defined as the ‘static labelling model’, allowing dynamic trials to be automatically labelled based on the pattern of markers seen in the static trial. Optimal settings were again chosen for the automatic labelling function using a trial-and-error approach, and this command was completed on all dynamic trials. Despite the optimal settings being selected, the automatic labelling function often produced small errors in the model that required manual correction. As a result of this each trial was manually checked for the quality of dynamic labelling, and any errors corrected manually.

Markers that become occluded during part of a trial also required 'defragmenting'; undergoing a gap filling protocol to ensure it is present throughout the trial. Without this procedure certain processing later in the protocol, for example tracking a segment of three markers, would be impossible due to missing marker trajectories. Gaps in a marker's trajectory can be filled in two ways; either a spline fill or by copying the trajectory pattern of an adjacent marker. Spline fills are liable to error in movements that are not of a smooth nature or suddenly change direction or acceleration, as well as errors when filling a large gap, thus the concept of copying adjacent marker trajectories was employed. For example, if the medial ankle marker was occluded for a period of time, the trajectory of the lateral ankle marker was copied and applied to fill the gap in the trajectory of the medial marker, as it most likely follows a similar movement trajectory.

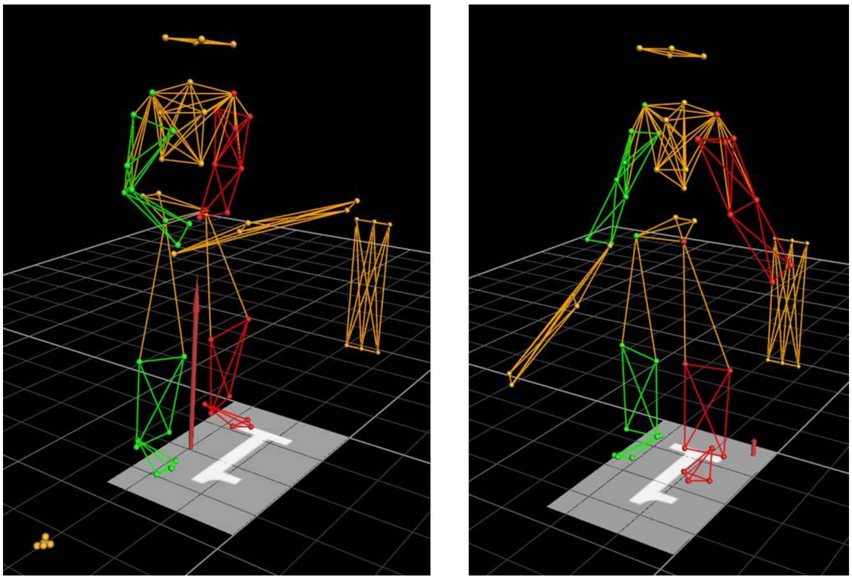


Figure 4.5: Two static trials tested as labelling models: batsman in their stance (left) and batsman in the anatomical position (right).

While this technique was successful at filling gaps where a marker became occluded in the middle of a trial, it does not allow gaps at the start or end of a trial (where the marker is not in view for the very first or very last frame) to be filled. This was sometimes the case with the medial ankle and knee markers, which became occluded at the start of the trial due to the position of the batsman's legs in his stance. In order to fill these gaps a code was written in Body Language (Vicon Motion Systems, Oxford, UK) that uses relationships between four markers placed on a single segment in the static trial to define where a missing marker should have been on a frame by frame basis. This code, termed 'replace4' relies on a generic macro command that is then called along with a definition of the four markers to be used.

As well as filling gaps at the start and end of the dynamic trials, the Body Language code was used to define and create a 'ball centre' marker, simply termed 'BALL'. This was defined as being the average of the visible ball markers on a frame by frame basis. On occasions when less than three ball markers were visible in one frame of data, the ball centre marker was not created to avoid significant errors in ball centre calculation. An interpolation tool would be used later in order to fill these gaps in the ball data, as well as a filtering tool to smooth out any minor errors created by the calculation method. Finally, any unlabelled markers (either unwanted noise or ghost markers) were deleted using a built-in pipeline command.

4.3.3 Filtering and Interpolating Movement Data

All motion capture systems possess errors in positional and temporal data; this is unavoidable. These errors are also incredibly tough to differentiate from the actual movement data of interest. Two methods exist to manage these errors.

The first option is to ignore the errors as being random and therefore equal across all data. This is the simplest approach as no data processing has to occur after capture. The main limitation with this is that using raw position data to process velocities and accelerations via differentiation techniques becomes error strewn, due to a higher order increase in errors when differentiating (Woltring, 1995).

The second option is to attempt to remove or reduce this error with digital filtering techniques, either in the time or frequency domain. A low pass digital filter (in the time domain) is commonly used as it removes measured data components above a certain cut-off frequency. This technique assumes any movement above the cut-off frequency is too fast for the human to create, thus must be random noise, while anything below is actual biological movement. However, there is always an overlap between the frequencies associated with human movement and random noise, thus making the selection of the cut-off frequency critical. Selecting a cut-off frequency too high leaves unwanted noise in the signal, whereas selecting a cut-off frequency too low removes too much of the true signal, often affecting the meaningful results.

After all the gaps had been filled, marker data was interpolated and filtered using Visual 3D biomechanical software. Since gaps in the original marker trajectories had already been manually filled, the interpolation command was purely in order to fill any small gaps created in the ball centre location, using a third order polynomial interpolation tool.

A two-way Butterworth low-pass filter was applied to the raw marker data. Sample marker position data from three subjects was analysed using the residual analysis technique proposed by Winter (2009) in order to determine the optimal cut-off frequency for the filter. In this case it was vital that the chosen cut-off frequency was not too low such that data was over-smoothed and later analysis of marker and segment velocities and accelerations were affected, but not too high as to leave unwanted noise in the signal. This is particularly critical around the time of impact, where movement data is likely to contain higher frequencies of signal and noise.

As a result of this test a frequency cut-off of 15 Hz was chosen when filtering raw marker data (Figure 4.6). This value was compared to a similar analysis of optimum cut-off frequency using a Fourier analysis; while the Fourier analysis suggested slightly higher cut-off frequencies of 20 Hz, these methods are somewhat subjective, thus the similarity between findings is sufficient to justify their use. While this filtering method and cut-off value was found to be suitable when considering marker data from the batsmen themselves, these markers move relatively slowly in comparison to those on the bat and the ball, particularly around impact. As such, in the case of the bat and ball markers, the raw data was maintained and used for later analysis.

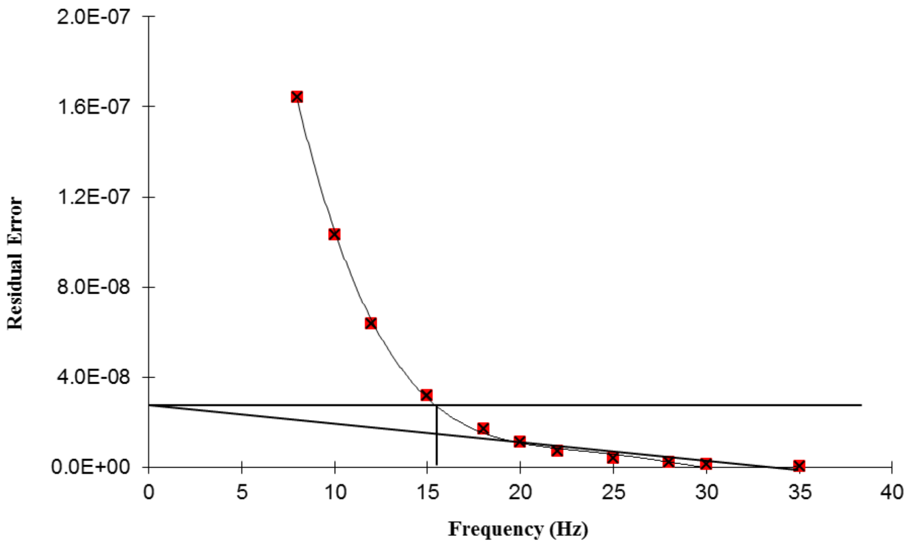


Figure 4.6: Residual error vs. cut-off frequency analysis for selection of the optimal cut-off frequency when filtering raw marker data.

4.4 Modelling Marker Data

Once filtered, the marker data could be used in a biomechanical model to extract kinematic and kinetic data. For this study a full body model was defined using Visual 3D; this was based on the static trial for each subject then applied to dynamic trials in turn. The software relies on a minimum of three markers to track a single segment in three-dimensional space, often using other markers as 'tracking' markers to increase redundancy should one of the original three markers fall out of view.

Visual 3D uses a 'segment optimisation' technique (based on the terminology of Lu and O'Connor (1999)) to determine segment lengths from the static trial and joint centre definitions. It assumes rigid segments and fixed segment lengths (calculated from the static trial) and applies these to the dynamic trials using a least squares fit to the marker data available. This is a significant improvement on the 'direct method' of segment definition, which simply calculates the segment position and size on a frame by frame basis using vectors from the origin marker to two other markers on the segment, as it takes skin movement artefact into account by removing its impact on certain aspects of dynamic movement at a purely segment level assuming it to be random noise. While there are still some issues with the segment optimisation technique, for example it treats segments individually without considering joint constraints, and skin movement patterns in adjacent segments can be very different creating errors and apparent joint dislocations and errors in joint centre axes, new approaches such as the ‘global optimisation method’ (Lu & O’Connor, 1999) are largely unproven and significantly more complex to implement, thus are not used in this study.

4.4.1 Model Segment Definitions

A 16 segment kinematic model of the human, bat, ball, and stumps was created in Visual 3D based on the marker set outlined in section 3.6. 13 rigid segments were used to define the human body: head and neck; thorax; pelvis; 2x upper arms; 2x forearms; 2 x thighs; 2x shanks; and 2x foot segments, along with a bat, ball, and set of stumps (Figure 4.7).

Segment definitions were determined through careful consideration of the movements the model must represent, and the desired kinematic outputs. A series of virtual landmarks were also created and added to the model; these were based on relationships with existing markers, and were included to allow better segment definition or to aid in generating the required outputs from the model. A three-dimensional coordinate system was then defined for each segment using marker locations from the static trial, allowing segment orientations and joint rotations to be calculated.

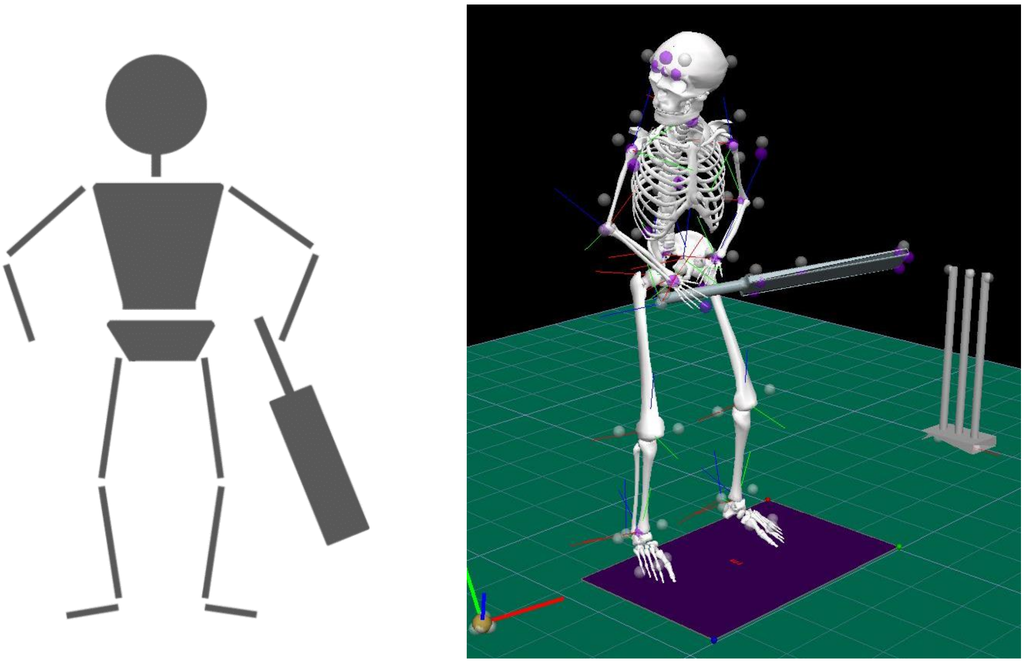


Figure 4.7: Model representation (left) and biomechanical model (right) based on marker data.

4.4.1.1 Pelvis Segment

The pelvis segment was defined using the CODA method via the two ASIS and two PSIS markers. The origin of the local coordinate system was placed at the midpoint of the two ASIS markers. The x-axis was defined by a vector from the origin laterally to the right ASIS marker defining the axis of anterior/posterior pelvic rotation, the y-axis running anteriorly defining the axis of lateral pelvic rotation, and the z-axis running superiorly along the longitudinal axis of the body defining the axis of transverse pelvic rotation.

From the pelvis segment definition, the two hip joint centres (RHJC, LHJC) were calculated based on the algorithms used by Bell et al. (1989):

$$RHJC = (0.36 * ASISdistance, -0.19 * ASISdistance, -0.3 * ASISdistance)$$

$$LHJC = (-0.36 * ASISdistance, -0.19 * ASISdistance, -0.3 * ASISdistance)$$

Where:

ASISdistance = the distance between the right and left ASIS markers

4.4.1.2 Thorax Segment

While the spine in reality is highly mobile and can experience a number of rotations which vary in magnitude along its length, often causing it to be modelled as several segments; in this case the thorax was modelled as a single segment. Initially, landmarks were created at the midpoint of the C7 and clavicle (C7_CLAV) markers, and the midpoint of the T10 and sternum (T10_STRN) markers.

The thorax segment was then defined with its origin at the C7_CLAV landmark, such that the longitudinal (z) axis ran superiorly along a line between the T10_STRN and C7_CLAV landmarks. The anterior-posterior (y) axis was then defined as a line perpendicular to the longitudinal axis passing through the sternum marker, and the lateral (x) axis as the line mutually perpendicular to the longitudinal and anterior-posterior axes, running to the right towards the shoulder joint centre. This segment definition was based largely on the recommendations made by the ISB (Wu et al., 2005), although some minor alterations have been made to facilitate its implementation in Visual 3D software and according to the marker set present, and allows for measurement of total thorax flexion/extension, lateral flexion, and transverse rotation throughout a movement.

4.4.1.3 Head and Neck Segment

Five additional virtual landmarks were created in order to define the head and neck segment, based on the four markers placed on the helmet (LFHD, RFHD, LBHD, and RBHD):

$$AnteriorHead = (LFHD + RFHD)/2$$

$$PosteriorHead = (LBHD + RBHD)/2$$

$$LeftHead = (LFHD + LBHD)/2$$

$$RightHead = (RFHD + RBHD)/2$$

A central head marker (HEAD) was then defined as the intersection between vectors joining the anterior & posterior, and the left & right head landmarks. The head and neck segment was then defined from the superior thorax landmark to the HEAD landmark at the centre of the four head markers. The origin was defined as the superior thorax landmark created previously, and the local coordinate system setup such that the z-axis ran longitudinally from the origin to the central head marker defining the axis of cervical rotation, with the y-axis running anteriorly defining the axis of lateral cervical flexion, and the x-axis running laterally defining the axis of cervical flexion/extension.

4.4.1.4 Thigh and Shank Segments

The midpoint of pairs of markers positioned across the joints defined the ankle and knee joint centres. Both the thigh and shank segments were defined such that when in an anatomical position, the z-axis pointed upwards defining the longitudinal axis, the x-axis pointed laterally defining the axis of flexion/extension, and the y-axis pointed anteriorly defining the axis of abduction/adduction. In this case the thigh segments were created with their proximal joint centres at the hip joints discussed in section 4.4.1.1, and their distal joints at the knee joint centre, while the shank segments ran from the knee joint centres to the ankle joint centres.

4.4.1.5 Foot Segments

Two distinct definitions of the foot segments were used in this model. The first and default definition of the foot segment (left and right foot) has the proximal end at the ankle, where the moment and force are computed for any inverse dynamics calculations that might be performed, and the distal end at the left or right toe (LTOE, RTOE) marker. This definition, however, creates an ankle with approximately 70° of dorsi-flexion in the anatomical pose, which is not the typical ankle angle as described in kinematic data.

Therefore, the second definition of the foot segment (left and right virtual foot) with its primary-axis defined from heel to toe marker, is useful for computing the kinematics of joint angles (C-Motion, 2015), as in a standing pose the ankle dorsi/plantar flexion angle is 0°. This foot segment definition has its origin at the heel marker (LHEE, RHEE), such that the x-axis runs laterally representing the axis of dorsi/plantar flexion, the y-axis runs anteriorly representing the axis of inversion/eversion, and the z-axis runs vertically representing any rotation about the longitudinal axis.

4.4.1.6 Upper Arm and Forearm Segments

The midpoint of pairs of markers positioned across the joints defined the shoulder, elbow, and wrist joint centres. Both the upper arm and forearm segments were defined such that when in an anatomical position, the z-axis defined the longitudinal axis of the segment, the x-axis pointed laterally defining the axis of flexion/extension, and the y-axis pointed anteriorly defining the axis of abduction/adduction. In this case the upper arm segments were created such that the proximal joint centre was located at the shoulder joint, and the distal joint at the elbow, while the forearm segments ran from the elbow to wrist joint centres.

4.4.1.7 Hand Segments

As discussed in section 3.6, markers on the hands/batting gloves of the batsmen were removed from the marker set. The hands were assumed to form a rigid link with the bat (Stuelcken et al., 2005; Tsunoda et al., 2004), thus the angle between the forearms and the bat handle could be taken as the wrist joint angle. As a result, no hand segments were specified in the biomechanical model, although hands were added to the animations using a virtual landmark created along the longitudinal axis of the forearm purely for visual purposes.

4.4.1.8 Bat Segment

The bat segment has its proximal end defined as the top of the handle, with its distal end as the midpoint between the two markers placed on the bottom of the blade, thus having its longitudinal axis running down the length of the bat defining any twist about the handle. The x-axis runs laterally, defining the primary axis of the bat swing, while the y-axis points posteriorly defining any lateral rotation.

4.4.1.9 Stumps and Ball Segments

The stumps are defined such that the origin is placed at the base of middle stump with the longitudinal (z) axis running vertically up to the top of middle stump. This segment does not move; thus it is more likely that simply the marker locations will be used rather than calculations involving the segment as a whole. While the ball was created as a segment in Visual 3D, analysis will purely focus on the ball centre location, which is assessed via the ball centre landmark discussed in section 4.3.2.

4.4.1.10 Segment Names

The 18 model segments have been named as follows:

- Head
- Thorax/Abdomen
- Pelvis
- Left thigh
- Right thigh
- Left shank
- Right shank
- Left foot
- Right foot
- Left virtual foot
- Right virtual foot
- Left upper arm
- Right upper arm
- Left forearm
- Right forearm
- Bat
- Ball
- Stumps

4.4.2 Joint Angle Definitions

Joint angles were primarily calculated using Cardan angles, specifying the rotation that must be applied to the proximal segment (parent) coordinate system to align it with the distal segment (child) coordinate system. In a number of situations, the lab coordinate system was used as the parent segment, for example to calculate pelvis and thorax rotation between two specific temporal events.

In general, joint rotation angles were calculated using an x-y-z Cardan sequence. This represents an initial rotation about the x-axis of the parent segment corresponding to flexion-extension, followed by rotation about a floating axis mutually perpendicular to the first and third axes corresponding to abduction-adduction, and finally rotation about the z-axis of the child segment corresponding to axial rotation (Robertson et al., 2013). While debate exists on the ideal rotation sequence to apply to the shoulder joint, and various recommendations have been made for a range of different rotation sequences (e.g. Wu et al., 2005 in collaboration with the International Society of Biomechanics), it was found that the default x-y-z Cardan sequence (as used by Worthington et al., 2013) produced seemingly meaningful results, thus was used for this application.

The only segments where a different rotation sequence was used was when considering rotations of the pelvis and thorax. Research by Baker (2001) suggests that if pelvic tilt (equivalent to flexion/extension) or lateral rotation (equivalent to abduction/adduction) are significant, using the conventional x-y-z Cardan sequence above results in errors in those two measures, and causes values to be produced that are not in agreement with a conventional clinical understanding of the segment. As such Baker suggests that the sequence of rotations for the Cardan angle description of the pelvis relative to the laboratory should be transverse rotation, lateral rotation, and tilt. This is the opposite of the conventional joint angle definition used to describe the angles of other joints in this model, relying in this case on a z-y-x Cardan sequence, and works to minimise errors found when using other rotation sequences. Rotations of the thorax segment were performed using the same z-y-x rotation sequence in order to maintain consistency when comparing with the pelvis segment. Positive angle changes and zero angle positions (in the anatomical pose) were defined as detailed in Table 4.2.

Table 4.2: Details of the joint angles calculated.

Joint	+ve x	Anatomical position (°)	+ve y	Anatomical position (°)	+ve z	Anatomical position (°)
Pelvis	Posterior rotation	0	Lateral rotation	0	Transverse rotation	0
Thorax	Extension	0	Lateral flexion	0	Transverse rotation	0
Knee; Elbow	Extension	180	Abduction	0	Longitudinal rotation	0
Hip	Extension	180	Abduction	0	Internal rotation	0
Shoulder	Flexion	0	Abduction	0	External rotation	0
Wrist	N/A	N/A	Uncocking	180	N/A	N/A

Due to the lack of markers on the hands, the angles of flexion/extension and abduction/adduction at the wrist could not be measured directly. However, as the hands were assumed to form a rigid link with the bat handle (section 3.6) the angle of cocking/uncocking of the wrists during the bat swing could be measured. This was defined as the angle generated between the forearm of the top hand (left forearm for right handed batsmen, right forearm for left handed batsmen) and the bat (Figure 4.8).

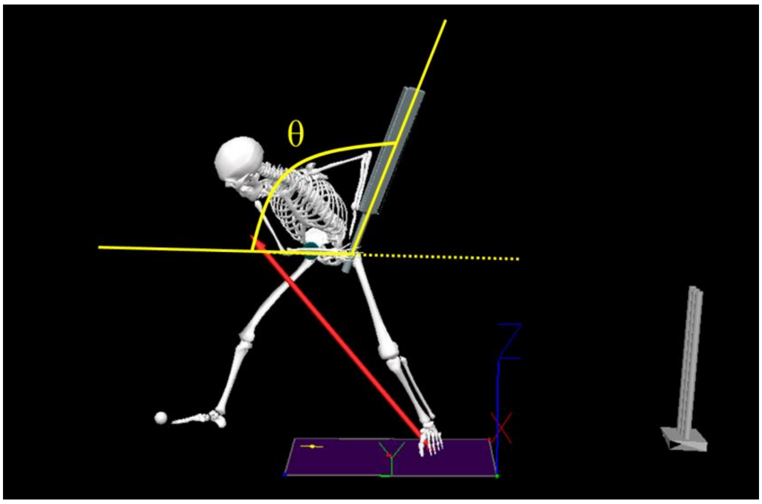


Figure 4.8: Wrist cocking angle generated between the forearm of the top hand and the bat.

4.5 Model Processing

Once the model had been built it was recalled and applied to the dynamic trials using a bespoke code written in Visual 3D software. A series of post modelling processing steps were then completed in Visual 3D in order to define events and extract values of interest from the motion data.

4.5.1 Assigning Tags to Files

Before any data processing and extraction was completed, files were given relevant tags using the Visual 3D software for identification during the later stages of analysis. This included tagging the subject number for each trial, the shot played and whether the subject was right or left handed. This allows for easy analysis and comparison within and between groups or shots in the future.

4.5.2 Defining Key Events

To effectively analyse batting shot kinematics and timings it is critical to accurately define discrete key instances in time for each shot where comparisons between repeated trials or groups of players can be easily made. A series of events have been defined for each trial these depend on the shot being played and the ball delivery method, and are presented below:

4.5.2.1 Key Events in the Forward Drive

The forward drive is probably the most commonly used attacking shot in cricket, and has a number of common events across different players and types of technique employed. A code has been written in Visual 3D to automatically identify these events from marker data in each dynamic trial, as well as a series of other events designed to assist in future processing and analysis. These are presented below in approximate chronological order (Table 4.3), although this changes from trial to trial, and then discussed in the order with which they were written and processed in the dynamic trials. The seven major events defining the motion of the forward drive are also presented in sequence in Figure 4.9. These events were also used in the range hitting analysis conducted in chapter 9.

Table 4.3: Key events in the forward drive.

Start	The first recorded frame of data
Impact -200	Arbitrarily defined as 200 frames (0.8 s) before the time of impact – used as a boundary event for identifying other key instances
Release	The time of ball release from the bowling machine, Sidearm or bowler's hand
Start of BS	The instant at which the batsman begins their final backswing before the transition into the downswing
FF Stride Start	The time at which the batsman began their major forward stride (ignoring any trigger movements)
Top of BS	The instant at which the batsman reaches the top of their backswing and begins to swing forward towards impact
FF Peak Height	The time at which the front foot reaches its peak height during the forward stride
Bounce	The time at which the ball bounces on its approach to impact
FF Stride End	The instant at which the batsman completes their forward stride
Impact	The point of contact between bat and ball – in the case of impact occurring between frames, the frame before impact was selected
Impact +3	Arbitrarily defined as three frames (0.012 s) after impact – this is used to calculate ball speed and direction
Impact +10	Arbitrarily defined as ten frames (0.04 s) after impact – this is used to calculate ball speed and direction
Impact +100	Arbitrarily defined as 100 frames (0.4 s) after the time of impact – used as a boundary event for identifying other key instances
End	The last recorded frame of data

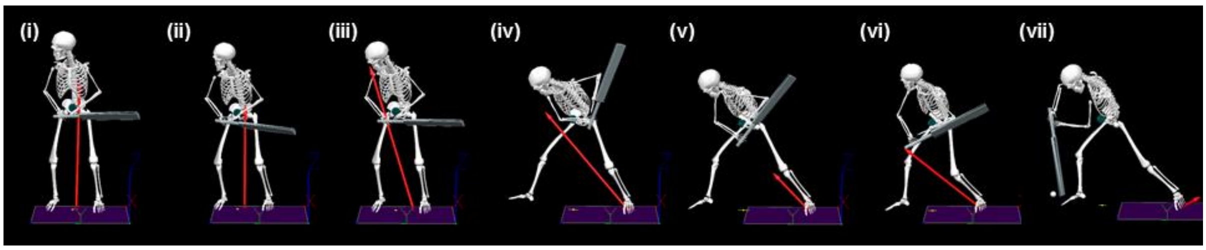


Figure 4.9: The seven key events in the forward drive identified from the biomechanical model (i) ball release; (ii) start of backswing; (iii) initiation of stride; (iv) start of downswing; (v) completion of stride; (vi) ball bounce and (vii) impact.

Initially the Start and End events were defined in the Visual 3D software (Figure 4.10); these were simply defined as the first frame (frame number 1) and as the ‘EOF’ or ‘end of file’, which creates an event label at the last frame of the recorded data.

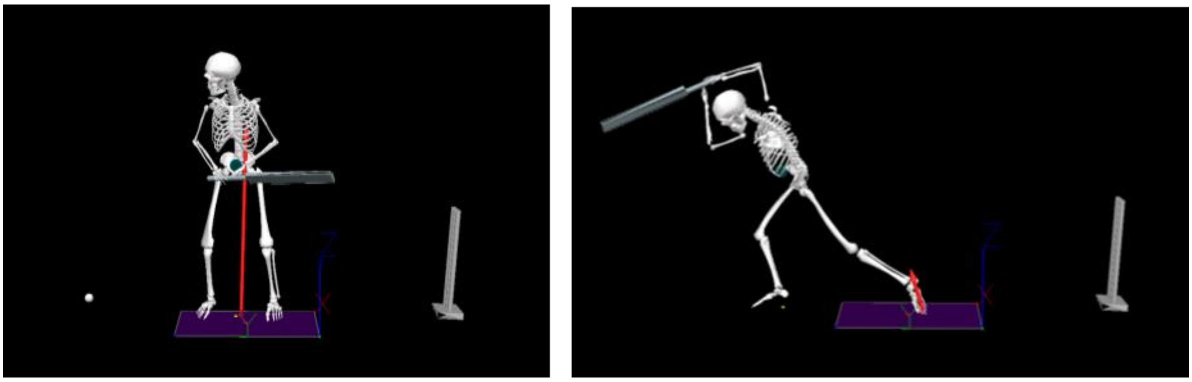


Figure 4.10: ‘Start’ (left) and ‘end’ (right) events for the forward drive.

Next the time of ball release, ball bounce and bat-ball impact were processed as events. The instant of ball release and bounce were determined from the high-speed videos and manually input into the individual dynamic trials in Visual 3D (Figure 4.11). In order to determine the time of impact, the velocity of the central ball marker was established using a first derivative. The impact event (Figure 4.12) was then placed at the instant this velocity switched from a negative Y velocity (towards the batsman) to a positive Y velocity (away from the batsman). Each impact event was then manually checked, and in cases where impact occurred between frames, the frame prior to impact was selected. For the static ball trials where the ball began stationary, a threshold ball velocity value of 5 ms^{-1} in the anterior-posterior plane was used to establish the time at which the ball began moving and hence the time of impact. A dummy release event was also included in the static ball trials, placed 25 frames (0.1 s) before the batsman’s first movement (start of the backswing or forward stride) in order to allow kinematic variable extraction at this time. Finally, for the initial bowling machine trials where the ball could not be tracked using the Vicon system and trials where contact was not made with the ball, the impact time was determined from the high-speed video and Vicon data and manually inputted into the dynamic trials.

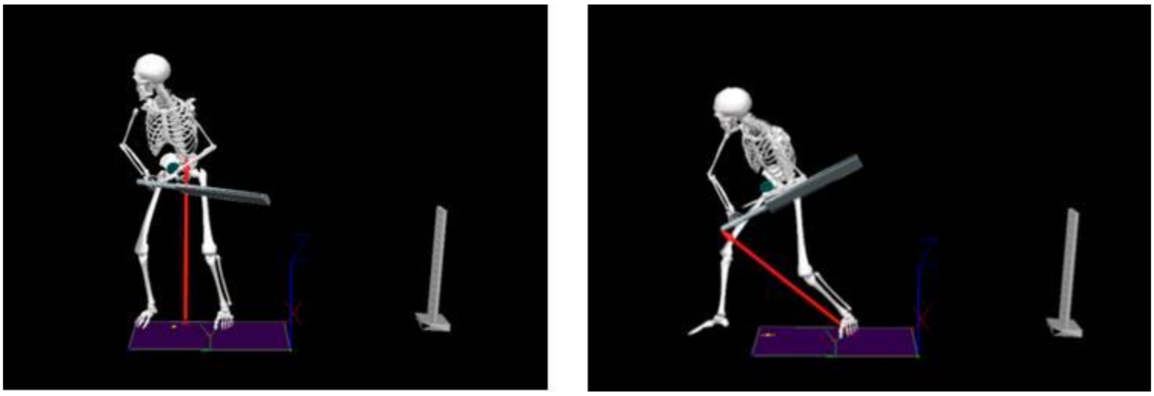


Figure 4.11: Release' (left) and 'bounce' (right) events for the forward drive.

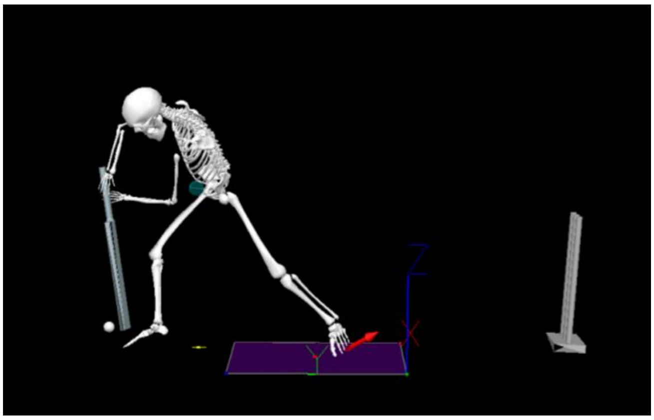


Figure 4.12: 'Impact' event for the forward drive.

The 'event copy' tool in Visual 3D was then used to place events at set times before and after impact. An arbitrary event was placed at 200 frames (0.8 s) before the time of impact, and another at 100 frames (0.4 s) after impact. These were simply used as boundary events in order to assist with identifying later events. Events were also created at three (0.012 s) and ten (0.04 s) frames following impact; these were used to assess post-impact ball speed and direction.

Next the timings of the forward stride were determined (Figure 4.13). Initially the point at which the front foot reached its peak height (Z-axis) between 'Impact -200' and impact was found and created as an event. This defines approximately the midpoint of the forward stride, and as a boundary event allows for more reliable determination of the start and end points of the stride. The instant of the player commencing their major forward stride was assessed using a threshold value placed on the forward velocity of the front foot in the anterior-posterior plane. The last point at which, before the foot reached its peak height, the forward velocity surpassed 0.1 ms^{-1} was characterised as the start of the forward stride. This meant that any previous times the foot velocity exceeded this value, for example in a trigger movement, were not confused with the start of the major pre-impact forward stride.

The end of the forward stride was defined as the first point after the foot reaches its peak height at which the sum of its angular and linear velocities fell below a threshold, indicating the time the foot was flat and stationary on the floor. This was done by creating a signal summing the magnitude of the angular velocity of the front foot with the linear velocity of its centre of mass in the anterior-posterior plane, then creating the event when the value of this signal fell below two (determined from repeated trial and error methods). Segmental centre of mass was calculated in Visual 3D by defining each segment as a geometric shape (cone, cylinder, sphere, or ellipsoid) with a default mass relative to the total body mass. This allows the centre of mass location of each segment to be calculated on a frame-by-frame basis. Inertia estimates were also calculated as standard based on the segment geometry and the proximal and distal radii of the defined segment (C-Motion, 2014).

While the front foot peak height event was not used in future analysis, it was essential in ensuring the stride start and end events were reliably placed at the correct points in time. Although previous research has identified the timing of heel strike and front foot flat on the floor (Stuelcken et al., 2005), not all players in this study exhibited a heel strike approach, thus just the timing of front foot flat was used.

Having established the event timings of the forward stride, the final set of events processed in the Visual 3D code were regarding the bat motion. An event was placed at the top of the backswing; this was defined as the final point before impact that the bat rotational velocity about the intended axis switched from a negative (backwards) to a positive (forwards) direction. Again by using the impact event as a boundary event, any previous movement of the bat for example in a trigger movement is ignored and the correct top of backswing event is identified. An event was also placed at the start of the backswing, defined as the final point before the top of the backswing at which the bat rotational velocity about the global medio-lateral axis switched from positive (forwards) to negative (backwards) (Figure 4.14). This differentiates the backswing from any initial backlift or movement of the bat in the preparatory phase.

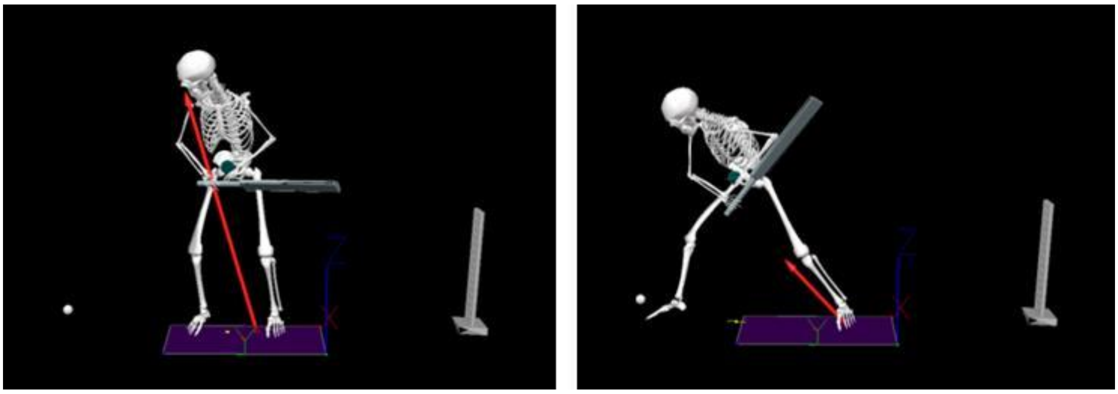


Figure 4.13: 'Stride start' (left) and 'stride end' (right) events for the forward drive.

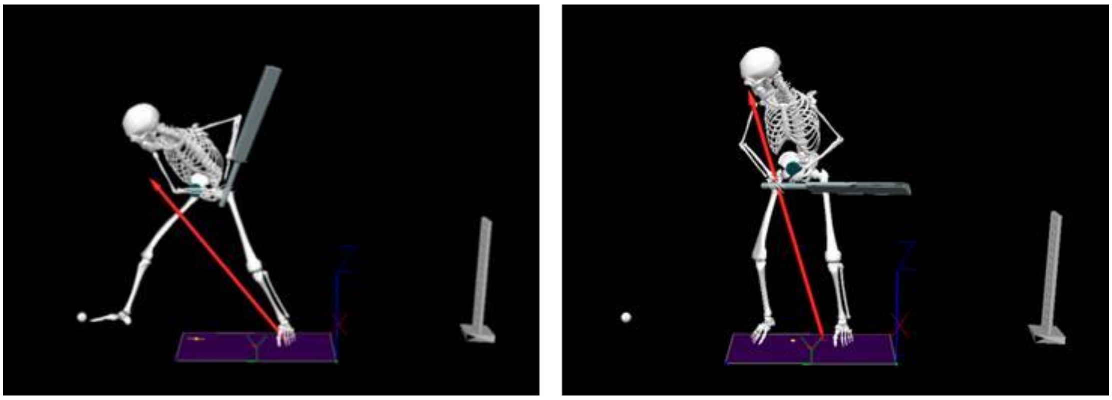


Figure 4.14: 'Top of backswing' (left) and 'start of backswing' (right) events for the forward drive.

4.5.2.2 Key Events in the Pull Shot

The pull shot is another popular attacking shot played by cricket batsmen, and as with the forward drive it has a number of common events and technical similarities when played across a range of players. Again a code was written to automatically identify a series of events within each dynamic trial; these are presented in approximate chronological order below (Table 4.4), and any events that are unique to the pull shot or defined in a different way than in the forward drive are discussed in more detail. The seven major events defining the motion of the pull shot are also presented in sequence in Figure 4.15.

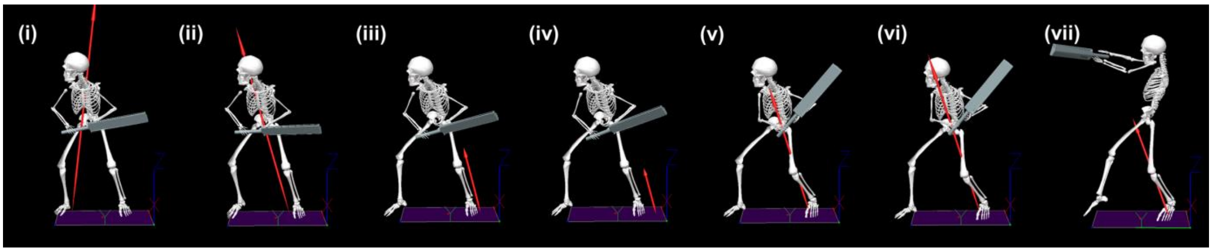


Figure 4.15: The seven key events in the pull shot identified from the biomechanical model (i) ball release; (ii) start of backswing; (iii) ball bounce; (iv) back weight transfer; (v) start of downswing; (vi) hands forward and (vii) impact.

Table 4.4: Key events in the pull shot.

Start	The first recorded frame of data
Impact -200	Arbitrarily defined as 200 frames (0.8 s) before the time of impact – used as a boundary event for identifying other key instances
Release	The time of ball release from the bowling machine, Sidearm or bowler's hand
Start of BS	The instant at which the batsman begins their final backswing before the transition into the downswing
Bounce	The time at which the ball bounces on its approach to impact
Back Weight Transfer	The point at which the batsman transfers their weight from forwards to backwards
Top of BS	The instant at which the batsman reaches the top of their backswing and begins to swing forward towards impact
Hands Forward DS	The point at which the players' hands switch from travelling backwards in the backswing to forwards in the downswing – different definition of top of backswing/start of downswing
Impact	The point of contact between bat and ball
Impact +3	Arbitrarily defined as three frames (0.012 s) after impact – this is used to calculate ball speed and direction
Impact +10	Arbitrarily defined as ten frames (0.04 s) after impact – this is used to calculate ball speed and direction
Impact +100	Arbitrarily defined as 100 frames (0.4 s) after the time of impact – used as a boundary event for identifying other key instances
End	The last recorded frame of data

As with the forward drive event processing, initially the start and end of frames events were created, followed by manually inputting the ball release and bounce events determined from the high-speed video. Because the pull shot is aimed to be hit approximately perpendicular to the direction of the inbound delivery, some trials maintained their negative velocity in the y-axis after impact. This made the time at which the ball's velocity in the y-axis switched from a negative to a positive measure, as used to determine the impact time in the forward drive, an unsuitable method. A threshold method was also trialled to identify the time at which the ball's velocity in the x-axis increased dramatically, indicating the point of impact, although this produced a number of errors when trialled. As a result, the impact event was also inputted using timings determined from the high-speed video and Vicon data. Following the impact event being processed, arbitrary events placed 200 frames (0.8 s) before and three (0.012 s), ten (0.04 s), and 100 (0.4 s) frames after impact were again created. A dummy release event was also included 25 frames (0.1 s) before the batsman's initial movement to allow kinematic data extraction at this time, as in the forward drive event processing (section 4.5.2.1).

Next the timings of the bat swing were determined. The start of backswing and top of backswing events were identified using the same methods as in the forward drive above. However, a second definition of the transition from backswing to downswing was also employed for the pull shot, based on the work of Escamilla et al. (2009a, 2009b). These authors suggested that using the point at which the hands switched from moving in a backward direction to a forward direction was a more suitable method for identifying the commencement of the downswing in a baseball swing. Due to the similarities between the baseball swing and the pull shot, this event definition was added to the code for later analysis and comparison with the existing definition of the top of backswing from the forward drive analysis (Figure 4.16).

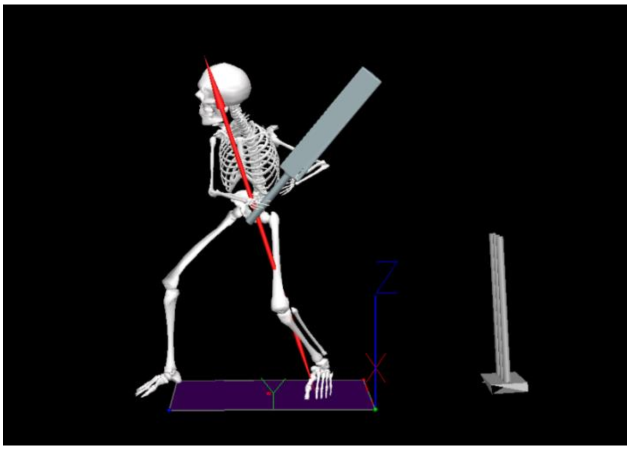


Figure 4.16: 'Hands Forward DS' event in the pull shot.

Finally, the time at which the batsman transferred his weight from forwards to backwards during the batting shot was determined. This was determined via displacement of the whole body centre of mass landmark calculated in Visual 3D, calculated via a summation of individual segment centre of mass locations on a frame-by-frame basis. Players were found to initially transfer the weight forwards onto the front foot, before transferring onto the back foot in approach to bat-ball impact. The point at which the whole body centre of mass velocity switched from a forward (positive Y) direction to a backward (negative Y) direction was defined as the event timing (Figure 4.17).

While commonalities exist in the stride stage of the forward drive, investigation of a range of pull shot techniques found batsmen to exhibit a variety of foot movement patterns. These ranged from the traditional back and across step, to stepping forward, pivoting on the back leg, or simply standing still and hitting. This made the definition of any common event involving the foot movement across all subjects impossible, hence the lack of such events in the Visual 3D code.

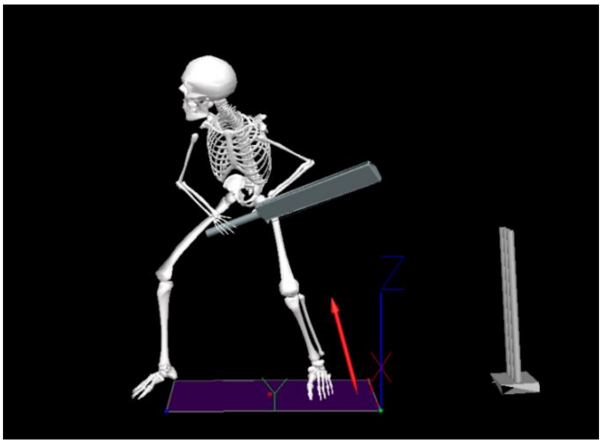


Figure 4.17: 'Back Weight Transfer' event in the pull shot.

4.5.3 Variable Definition

Having defined a number of key event instances in the forward drive and pull shots, a range of variables were defined in order to address the research questions discussed earlier (chapter 1). These were subdivided into three distinct categories; delivery characteristics (Table 4.5), event timings and movement durations (Table 4.6), and kinematic features of the movement (Table 4.7), which are presented below along with a brief definition of each. Variables were automatically calculated using a series of codes written for each batting shot, and with differing definitions for left and right handed batsmen in Visual 3D software, and a subset was then used in each analysis conducted throughout the study. Variables were very similar across analysis of the forward drive and pull shots, hence are included together in the tables below. Kinematic variables used in the analysis of range hitting were the same as those used throughout the analysis of the forward drive. Some of the kinematic variables were also calculated at a number of time points throughout the hitting action, and in a number of cases these were used to calculate rotation magnitudes of a segment between two events.

Table 4.5: Delivery characteristics variables assessed during the forward drive.

Variable	Definition
Ball speed (ms^{-1})	The speed of the ball post-release as measured by the Trackman unit
Release to impact time (s)	The time from ball release to impact
Bounce time (s)	The time from ball bounce to impact
Ball position at impact (m)	The position of the ball at the time of impact with the bat relative to the base of middle stump

Table 4.6: Event timing and movement duration variables assessed during the forward drive.

Variable	Definition
Start of backswing (s)	The time from the start of backswing to impact (or from ball release)
Stride start (s)	The time from the initiation of the forward stride to impact (or from ball release) – forward drive only
COM back (s)	The time from the point at which batsmen begin to transfer their weight backwards to impact
Start of downswing (s)	The time from the start of the downswing to impact (downswing duration)
Stride end (s)	The time from the completion of the forward stride to impact – forward drive only
Maximum X-factor (s)	The time from the moment at which the measured angular separation between the pelvis and thorax segments in the frontal plane (X-factor) reaches its maximum to impact
Maximum Z-factor (s)	The time from the moment at which the measured angular separation between the pelvis and thorax segments in the transverse plane (Z-factor) reaches its maximum to impact
Movement initiation time (MIT) (s)	The time from ball release to the first movement event (start of backswing or forward stride)
Stride duration (s)	The time between the initiation and completion of the forward stride
Backswing duration (s)	The time between the start of the backswing and the start of the downswing
Total movement time (s)	The time from the first movement event (start of backswing or forward stride) to impact

Table 4.7: Kinematic variables assessed during the forward drive.

Variable	Definition
Base width (m)	The distance in the X and Y planes between the centre of mass of the front and back feet
Base width (% of shoulder width)	The base width defined previously measured as a percentage of the distance between the two shoulder joint centres
COM position (% of base)	The position of the centre of mass as a percentage between the centre of mass of the front and back feet
Front shoulder position Y relative to the front foot (m)	The position of the front shoulder joint centre in the global anterior-posterior plane relative to the centre of mass of the front foot
Front knee position Y relative to the front foot (m)	The position of the front knee joint centre in the global anterior-posterior plane relative to the centre of mass of the front foot
Head position Y relative to the front foot (m)	The position of a virtual point between the eyes in the global anterior-posterior plane relative to the centre of mass of the front foot
Head position x relative to the	The position of a virtual point between the eyes in the global medio-

middle stump (m)	lateral plane relative to middle stump
Knee angle X (°)	A measure of the degree of flexion/extension at the front and back knee joints
Hip angle X (°)	A measure of the degree of flexion/extension at the front and back hip joints
COM height (m)	The height of the whole body centre of mass above the floor surface
Pelvis angle X (°)	A measure of the anterior/posterior rotation of the pelvis segment relative to the global coordinate system
Pelvis angle Y (°)	A measure of the lateral rotation of the pelvis segment relative to the global coordinate system
Pelvis angle Z (°)	A measure of the transverse rotation of the pelvis segment relative to the global coordinate system
Thorax angle X (°)	A measure of the anterior/posterior rotation of the thorax segment relative to the global coordinate system
Thorax angle Y (°)	A measure of the lateral rotation of the thorax segment relative to the global coordinate system
Thorax angle Z (°)	A measure of the transverse rotation of the thorax segment relative to the global coordinate system
X-factor (°)	The angular separation between the pelvis and thorax segments in the frontal plane (corresponding to flexion/extension)
Z-factor (°)	The angular separation between the pelvis and thorax segments in the transverse plane
Trigger movement	The preliminary movement used by the batsman pre-release (assessed subjectively)
Foot movement	The style of foot movement used by the batsman during execution of the pull shot only (assessed subjectively)
Bat angle X (°)	The angle of the bat about the global medio-lateral axis (corresponding to the main axis of rotation in the forward drive)
Bat angle Y (°)	The angle of the bat about the global anterior-posterior axis (corresponding to rotation towards and away from the off-side)
Bat angle Z (°)	The angle of the bat about the global vertical axis (corresponding to the longitudinal rotation of the bat
Bat COM height (m)	The height of the centre of mass of the bat, determined from the bat measurements taken during data collection
Wrist height (m)	The height of the wrist joint centres above the floor surface
Wrist cocking angle (°)	The angle formed between the bat and the forearm of the top hand, corresponding to the cocking of the wrists
Elbow angle X (°)	A measure of the degree of flexion/extension at the front and back elbow joints
Shoulder angle X (°)	A measure of the degree of flexion/extension at the front and back shoulders
Shoulder angle Y (°)	A measure of the degree of abduction/adduction at the front and back shoulders
Shoulder angle Z (°)	A measure of the degree of internal/external rotation at the front and back shoulders
Stride length (m)	The distance in the X and Y planes between the centre of mass of the front foot at the start and the end of the forward stride
COM travel (m)	The distance between the whole body centre of mass position at two events in a given plane
Head travel (m)	The distance between the head position at two events in a given plane
Bat angular velocity (°s^{-1})	The measured bat angular rotation velocity about the global medio-lateral (X) axis throughout the swing
Bat speed (ms^{-1})	The measured resultant bat distal endpoint speed throughout the swing

Back foot drag (m)	The distance between the position of the centre of mass of the back foot at the completion of the front foot stride and impact
Bat COM position Y relative to the front knee (m)	The position of the bat centre of mass in the global anterior-posterior plane relative to the centre of mass of the front knee
Bat COM position Y relative to the front foot (m)	The position of the bat centre of mass in the global anterior-posterior plane relative to a virtual point between the eyes
Follow through style	The style of follow through used; checked or full (subjectively assessed – forward drive only)
Ball speed (ms^{-1})	The ball speed calculated by differentiation of ball centre position between three and ten frames (0.012 to 0.04 s) after impact
Ball position at impact (m)	The position of the ball centre virtual marker at the time of impact – either height above the floor surface or relative to middle stump
COM forward velocity (ms^{-1})	The velocity of the whole body centre of mass in the global anterior-posterior and medio-lateral planes
Pelvis angular velocity X ($°s^{-1}$)	A measure of the angular velocity of the pelvis segment corresponding to anterior/posterior rotation
Pelvis angular velocity Z ($°s^{-1}$)	A measure of the angular velocity of the pelvis segment corresponding to transverse rotation
Thorax angular velocity X ($°s^{-1}$)	A measure of the angular velocity of the thorax segment corresponding to anterior/posterior rotation
Thorax angular velocity Z ($°s^{-1}$)	A measure of the angular velocity of the thorax segment corresponding to transverse rotation
Upper arm speed (ms^{-1})	The measured resultant endpoint speed of the front or back upper arm
Forearm speed (ms^{-1})	The measured resultant endpoint speed of the front or back forearm

A series of impact variables and post-impact ball launch parameters were also calculated and used for later analysis (Table 4.8). These were used throughout future analyses as measures of shot success. Post-impact ball launch parameters (speed and angle) were calculated using raw, unfiltered ball position data from the motion capture system; any filtering or smoothing around the time of impact is likely to affect the accuracy of these measures. The impact location of the ball on the bat was determined using the impact location code described in chapter 6. This calculation was not possible for all sets of trials due to the lack of ball tracking in some parts of the first data capture session, and as such impact location was only calculated for the range hitting and static ball trials (section 3.9.2).

Finally, ball carry distance was assessed for the range hitting trials using a bespoke iterative ball flight model developed for this study (Chapter 6). This model made a series of assumptions regarding the mass, cross-sectional area and drag coefficient of the ball, as well as the density of air and the absence of spin on the ball. The model used post-impact ball position data from the motion capture system to calculate launch parameters, and therefore the forces and accelerations experienced by the ball on a frame by frame basis. This was used to iteratively adjust ball velocity and therefore position, and calculate the distance the ball would have travelled before impacting the ground. This model was validated by tracking the motion of a series of trials fired outside from a bowling machine (n = 24) and measuring their resultant carry distance. The model was found to consistently under-predict the carry distance by -5.3 ± 2.4 m, and as such the drag coefficient of the ball used in the model was adjusted (from 0.45; Baker, 2009; to 0.34) throughout the analysis in order to account for this, reducing the difference between the predicted and measured carry distance to -0.2 ± 2.2 m. This model was then applied to the range hitting trials in order to calculate total resultant ball carry distance.

Table 4.8: Impact variables and post-impact ball launch parameters calculated throughout the study.

Variable	Definition
Ball speed (ms^{-1})	The post-impact resultant ball speed determined via differentiation of ball position data
Vertical launch angle (°)	The vertical post-impact angle of the ball relative to the pitch surface determined from ball position data
Horizontal launch angle (°)	The horizontal post-impact angle of the ball relative to the global coordinate system (i.e. middle stump to middle stump) determined from ball position data
Impact location X (m)	The distance of the ball centre from the sweetspot of the bat (Bower, 2012) in its medio-lateral plane at the time of impact, calculated using the curve fitting methodology outlined in chapter 6
Impact location Y (m)	The distance of the ball centre from the sweetspot of the bat (Bower, 2012) in its vertical plane at the time of impact, calculated using the curve fitting methodology outlined in chapter 6
Ball carry distance (m)	The calculated total resultant carry distance of a ball hit in the air, calculated using an iterative ball flight model

4.6 Chapter Summary

This chapter has described the data processing steps which were undertaken prior to and following the capture of subject motion capture data. Initially the calibration stages the motion capture system was taken through are outlined, and the accuracy of the system assessed. The data reconstruction and labelling process is then described, and the 13 segment kinematic model applied to the data defined. Finally, the definitions of joint angles and individual timing events and kinematic variables used throughout the later analyses are presented.

CHAPTER 5

A BIOMECHANICAL DESCRIPTION OF THE FORWARD DRIVE AND PULL SHOTS

5.1 Chapter Outline

This chapter aimed to provide a description of the kinematics of the forward drive and pull shots based on the kinematic data capture methodology outlined in Chapters 3 and 4, and introduce the kinematic variables used throughout the remainder of the studies. This will begin to highlight areas of batting technique warranting further study, and potentially identify important factors for consideration in coaching and player development. Because of the number of trials completed against each delivery method, and the variation in technique displayed by each player against each (Chapter 8), only the shots against the bowling machine were assessed in this section. A number of variables previously reported in the literature, as well as some new variables are discussed. In addition to presenting mean values, an indication of the variation within the group of batsmen tested is provided via range and standard deviation measures, and comparisons are made to previous research and coaching literature. A series of specific questions are then addressed regarding relationships between different aspects of batting technique and the ball delivery characteristics found in previous research or from examination of the data. All data is adjusted to relate to a right handed batsman for ease of comprehension.

5.2 The Forward Drive

The forward drive can be considered to consist of five phases: the stance, backswing, forward stride, downswing to impact, and follow through (Figure 5.1). These phases were defined via a series of events described in section 4.5.2.1. While these phases are described separately in this review, in many situations they in fact occur simultaneously or overlap in their timings. The techniques used by the 29 batsmen who played forward drives ($n = 9.5 \pm 1.3$) against the bowling machine during this study are reported. Typical delivery characteristics for this set of drives are also described.

Figure 5.1: The forward drive - (A) stance phase; (B) backswing and forward stride; (C) downswing to impact; (D) follow through.

5.2.1 Delivery Characteristics

At the time of release, ball speed from the bowling machine as measured by the Trackman unit ranged from 72.7 – 83.6 mph (mean = 79.0 ± 4.2 mph), or 32.5 – 37.4 ms^{-1} (mean = 35.3 ± 1.9 ms^{-1}). This was not measured for all players and all deliveries due to logistical issues and occasional errors in the tracking of the device, although the values presented above represent a meaningful average of ball speeds from 16 of the 29 players tested. Although this release speed does not characterise truly fast bowling at an international level, it is substantially faster than any previous kinematic study involving three-dimensional data capture, and is representative of the speeds used by players and coaches in training.

The ball release to impact time, calculated from the high-speed video and motion capture data, was 0.481 – 0.614 s (mean = 0.547 ± 0.046 s). These values are similar to the typical times reported by Abernethy (1981). Ball bounce was found to occur on average 0.467 ± 0.051 s after ball release, and 0.080 ± 0.024 s before bat-ball impact. This equates to the ball pitching after an average of 85% of the total ball release to impact time, indicating a consistently full-pitched delivery suitable to play the forward drive. At the point of impact, the ball (averaged across the 168 trials with ball tracking) was positioned on average 0.247 ± 0.150 m outside the line of middle stump towards the off-side, and 0.406 ± 0.116 m above the pitch surface, representing a suitable position to execute a forward drive back past the bowler on the off-side.

5.2.2 Movement Timings

The mean timings of each key event across all 29 subjects who hit forward drives against the bowling machine are shown below (Figure 5.2). The backswing began 0.080 ± 0.180 s after ball release. The large standard deviation seen in this measurement is principally caused by a single subject whose backswing began prior to ball release; removal of this subject's data amends the mean timing of the start of the backswing to 0.112 ± 0.087 s after release. The start of the front foot stride occurred marginally after the start of the backswing, on average 0.132 ± 0.058 s after release, continuing for a duration of 0.357 ± 0.067 s, before ending 0.058 ± 0.050 s prior to impact. The timing of front foot placement was very similar to the findings of Stretch et al. (1998; 0.06 s before impact) and Stuelcken et al. (2005; 0.05 s before impact), although contrary to the work of Weissensteiner et al. (2011) in that it was more strongly coupled to the timing of ball bounce than the commencement of the downswing.

The backswing lasted for 0.282 ± 0.154 s, before undergoing a fluid transition into the downswing. Again the large standard deviation in the backswing duration is primarily due to the earlier backswing start displayed by a single subject; removal of this subject's data alters the mean backswing duration to 0.254 ± 0.069 s. The downswing began 0.186 ± 0.032 s prior to impact, during which phase each batsman was accelerating the bat into the contact point. This is similar to the downswing duration found by Stuelcken et al. (2005) for international batsmen in a match environment (0.160 ± 0.020 s), suggesting a similarity between the required movement speed of the batsmen in both studies. The low standard deviation displayed in this measure indicates a remarkably similar downswing time across all players tested, as found by Weissenteiner et al. (2011) amongst skilled batsmen.

Figure 5.2: Mean timings of key events in the forward drive.

5.2.3 The Stance Phase

Players had a mean stance width of 0.519 ± 0.082 m. This equated to 170 ± 36% of the players' shoulder width (the distance between the left and right shoulder joint centres). This is substantially wider than is advised by coaching literature (MCC, 1987; ECB, 2009; who recommend feet shoulder width apart), although supporting the work of Stuelcken et al. (2005) who found elite players to adopt a wider stance than recommended (0.460 ± 0.080 m) when batting against fast bowling. While the preliminary movements utilised by the batsmen tested were not identified automatically, a subjective analysis of the motion capture footage found 15 out of 29 players to exhibit some form of trigger movement, with the remaining 14 standing still prior to their primary forward stride. Of the 15 players who utilised a trigger movement, five moved both feet back and across towards the off stump prior to ball release, four moved their back foot back and across before initiating a forward press, a further four moved their back foot forward before the primary forward stride, with three of these also using a forward press after the back foot movement, one employed a simple forward press technique, and one moved only his back foot back and across towards off stump before stepping forward into the ball. This shows a marked increase on the three basic preliminary movements outlined by Woolmer (2008), displaying the spread of techniques preferred by current elite batsmen.

At the moment of release, the batsman's centre of mass was positioned forward of centre relative to the base of support, on average at 63 ± 9% of the distance from the back foot to the front foot. This supports the studies of Stretch et al. (1998) and Taliep et al. (2007), who found batsmen to position their centre of mass forward of centre relative to the base of support in the stance, although suffers from the same limitation of the batsman's pre-release knowledge of the ball bounce location, thus allowing players to start with their weight biased towards the front foot in anticipation of a full length delivery. Further investigation of how the setup and position of the batsman at the point of release when they are unsure of the length of the approaching delivery will provide an interesting comparison. This forwards weight distribution can be largely explained by the substantial levels of flexion exhibited in the thorax segment (-40 ± 8°), leaning the body down the pitch towards the bowler and towards the off-side. The thorax segment was also found to display a small amount of lateral flexion (-2 ± 4°) towards the bowler at the point of release. The front knee joint centre (0.007 ± 0.040 m), shoulder joint centre (0.011 ± 0.072 m), and a virtual point between the eyes (0.002 ± 0.075 m) were all found to be marginally further forward than the centre of mass of the front foot at the point of release in the global anterior-posterior plane, also indicating a forward leaning of the body. The same point between the eyes was also found to be positioned on average 0.063 ± 0.073 m outside the line of middle stump (towards the off-side) in the global medio-lateral plane, indicating that players on average preferred to get their head across to the line of off stump at the point of ball release.

Both knees were found to be flexed in the stance, with the front knee exhibiting a greater degree of flexion (142 ± 9°) than the back knee (147 ± 10°). The knees underwent a small amount of additional flexion between the stance and moment of release, flexing to 137 ± 8 and 141 ± 9° for the front and back knees respectively. The front (128 ± 12°) and back (138 ± 13°) hips were also flexed in the stance, and as with the knees they were found to flex further to 125 ± 11° and 137 ± 13° respectively at the point of release. This caused a drop in the whole body centre of mass height from 0.982 ± 0.042 m in the stance to 0.962 ± 0.038 m at the moment of ball release, perhaps displaying the batsman readying themselves for explosive movement in reaction to the approaching delivery. The pelvis and thorax were similarly aligned relative to the crease at the instant of ball release, both displaying rotations of 68 ± 8° about the global vertical axis (Figure 5.3). This shows players in general adopted a slightly open stance in preparation for the delivery of the ball, similar to the findings of Stuelcken et al. (2005), allowing them a clear two-eyed view of the approaching ball.

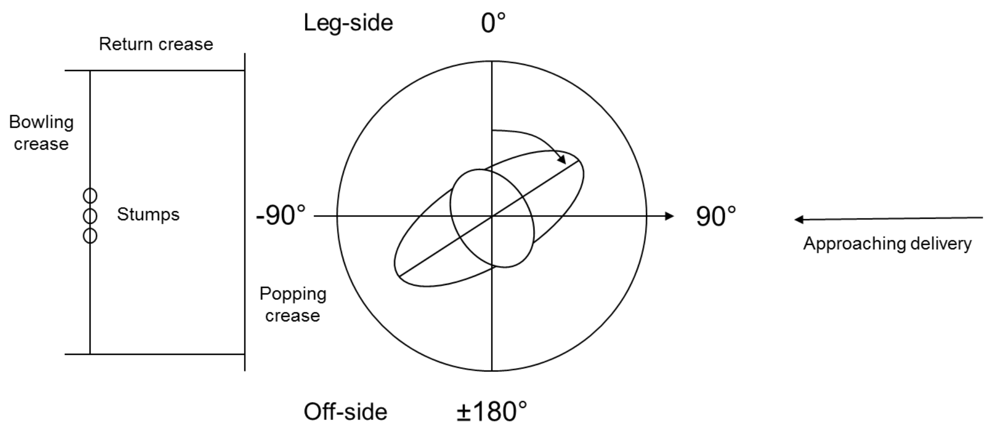


Figure 5.3: Pelvis and thorax angle Z - rotation of the pelvis and thorax segments about the global vertical axis (adapted from Stuelcken et al., 2005).

5.2.4 The Backswing

At the start of their backswing, players displayed a mean bat angle about the global medio-lateral axis (bat angle X) of -109 ± 23° (Figure 5.4), forming an angle with the top forearm (relating to the angle of cocking at the wrists) of 129 ± 14°. This equated to a bat centre of mass height of 0.917 ± 0.160 m above the pitch surface. At this instant the top and bottom wrist joint centres were positioned 0.866 ± 0.066 m and 0.950 ± 0.093 m above the pitch surface respectively, and the bat was angled towards the off-side about both the global anterior-posterior (-12 ± 10°; bat angle Y – Figure 5.5) and vertical (-20 ± 18°; bat angle Z – Figure 5.6) axes. Both the front (114 ± 18°) and back (81 ± 14°) elbows were flexed, with the back elbow showing a greater degree of flexion.

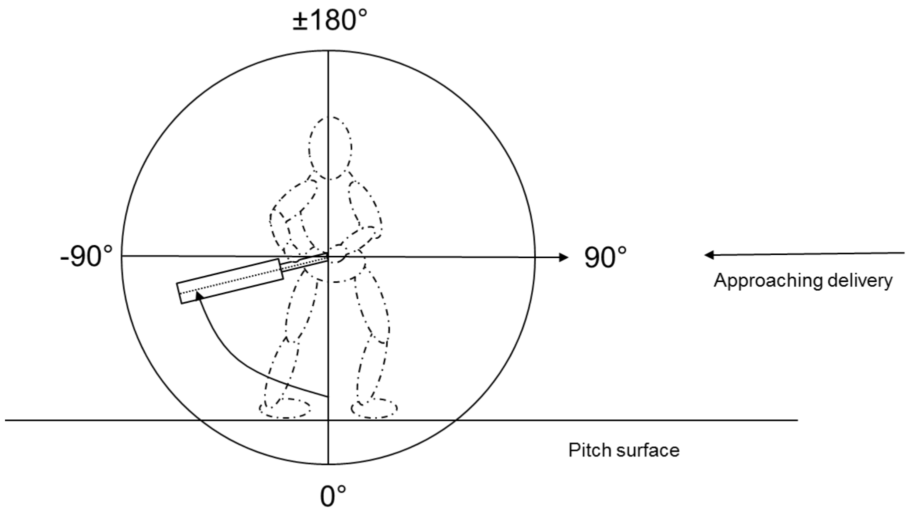


Figure 5.4: Bat angle X – bat angle about the global medio-lateral axis.

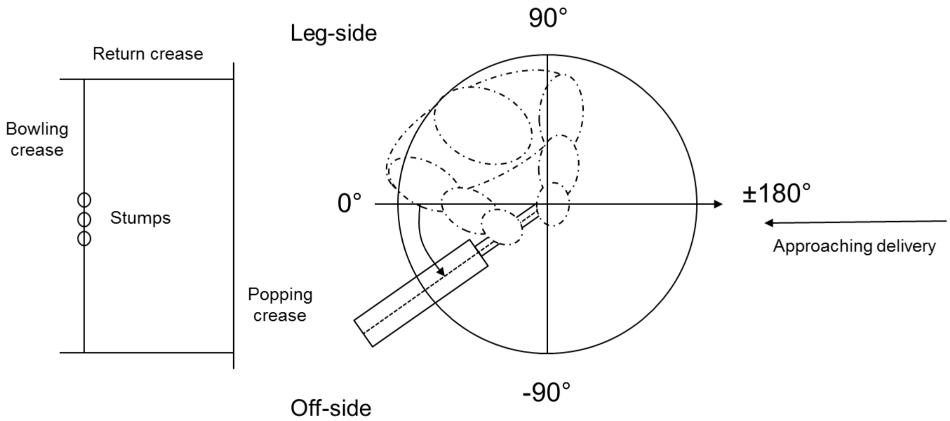


Figure 5.5: Bat angle Y – bat angle about the global anterior-posterior axis (adapted from Stuelcken et al., 2005).

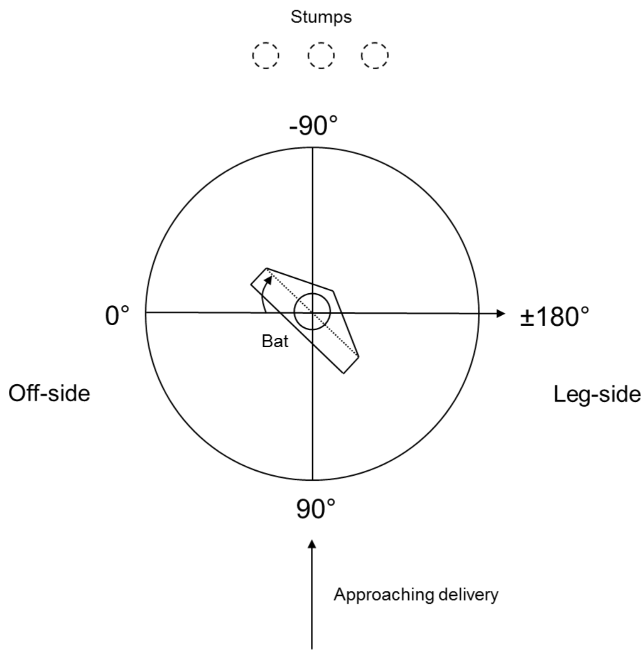


Figure 5.6: Bat angle Z – bat angle about the global vertical axis.

During the backswing itself, the thorax flexed forwards a further 11° (-43 ± 9° at the start of the backswing to -54 ± 6° at the top of the backswing). The bat was raised to an angle of -149 ± 13° about the global medio-lateral axis at the top of the backswing (Figure 5.4), elevating the bat centre of mass to 1.128 ± 0.094 m above the pitch surface. The bat also exhibited an increased angle towards the off-side about the global vertical axis (-33 ± 19°; Figure 5.6), indicating a more open face at this point. The bat angle about the global anterior-posterior axis (Figure 5.5) was found to decrease to a minimum of -16 ± 11° during the backswing, indicating an angling towards the off-side, before straightening up to -8 ± 8° at the top of the backswing. This indicates a slightly looped path of the bat during the backswing, similar to findings from elite batsmen by Stuelcken et al. (2005), and contrary to the recommendations of current coaching literature (MCC, 1987; Woolmer, 2008), who suggest a straight backswing directly over the stumps aids in bringing the bat down straight throughout the downswing.

In order to create the backswing movement, batsmen exhibited extension and adduction at the back shoulder (-21 ± 10° extension, -9 ± 7° adduction), while displaying flexion and adduction at the front shoulder (-3 ± 10° flexion, -19 ± 10° adduction). Both the front (-3 ± 6°) and back (-22 ± 11°) shoulders were found to internally rotate during the backswing, while a small amount of additional flexion in the front (1 ± 13°) and back (21 ± 14°) elbows was also exhibited. This caused the wrist joint centres to move an average of 0.087 ± 0.044 m towards the off-side away from the batsman's body in the global medio-lateral plane, and 0.019 ± 0.080 m forwards towards the batsman's back hip in the global anterior-posterior plane, relative to their position at the start of the backswing. The vertical displacement of the bottom wrist above the pitch surface increased by 0.082 ± 0.069 m during the backswing, while the top wrist remained at a similar height, rising by only 0.004 ± 0.060 m. The angle between the bat and the top forearm also decreased by 9°, reaching 120 ± 8° at the top of the backswing, indicating an increased cocking of the wrists during the backswing. Overall this provides strong evidence that elite batsmen utilise a levered backswing (as suggested by Stuelcken et al., 2005), keeping the hands close to the body while using a cocking motion at the elbows and wrists to lift the bat to the desired height and angle.

At the top of the backswing the pelvis had begun to rotate anti-clockwise about the global vertical axis, reaching a more front-on angle of 55 ± 8° (Figure 5.3). This generated an angular separation between lines defining the medio-lateral planes of the pelvis and thorax segments (Z-factor) of 10 ± 5°. The lateral flexion displayed in the thorax segment had decreased to -6 ± 5°, indicating a more substantial leaning of the upper body towards the bowler at the top of the backswing. A substantial angular separation (25 ± 9°) between the pelvis and thorax segments was also found about the global medio-lateral axis (X-factor) at the top of the backswing, with the thorax displaying greater forwards flexion (-54 ± 6°) than the pelvis segment (-29 ± 9°).

5.2.5 The Forward Stride

Batsmen exhibited a mean stride length of 0.396 ± 0.125 m, giving them a base length at the end of the front foot stride of 0.867 ± 0.114 m. During the stride, the centre of mass travelled 0.241 ± 0.088 m forward in the global anterior-posterior plane, and 0.048 ± 0.033 m down in the global transverse plane from its position at the start of the stride. Thorax flexion was also found to have decreased by 8° between the top of the backswing and the completion of the front foot stride to -45 ± 11°, although the centre of mass was still positioned forward of centre relative to the base of support, at 63 ± 5% of the distance from the back to front foot (as recommended by coaching literature; MCC, 1987; Woolmer, 2008; ECB, 2009). As a consequence of the forward stride, the front knee joint centre (-0.077 ± 0.044 m), shoulder joint centre (-0.167 ± 0.112 m), and a point between the eyes (-0.101 ± 0.110 m) were all found to be positioned backward of the front foot in the global anterior-posterior plane at the end of the front foot stride. Both the front (153 ± 11°) and back (151 ± 14°) knees were found to have moderate degrees of flexion at the completion of the front foot stride, although considerably less than at the moment of release. The front hip continued to flex throughout the stride causing the continued forward motion of the centre of mass, reaching 119 ± 9° at the moment of stride completion, while the back hip extended from its position at ball release to 168 ± 16°.

5.2.6 The Downswing to Impact

During the downswing the bat reached a maximum angular velocity about the global medio-lateral axis of 1373 ± 162°s^{-1}, equating to a maximum resultant linear distal endpoint speed of 19.16 ± 1.75 ms^{-1}, and reaching an angle of -24 ± 9° (Figure 5.4) at the time of impact. This bat speed is similar to the findings of Stuelcken et al. (2005) for international batsmen in match conditions (mean peak bat endpoint speed = 21.2 ms^{-1}), indicating the realistic nature of the test setup to match conditions. The angular separation between the pelvis and thorax segments in the frontal plane (X-factor) increased to a maximum of 26 ± 10° during the downswing 0.146 ± 0.059 s before impact, before both segments began to rotate backwards (posterior pelvic rotation and spinal extension) as the bat was swung through on its approach to impact. At the point of impact, the angular separation had reached 16 ± 10° indicating that the thorax segment was still rotated further forwards (-37 ± 12°) than the pelvis (-20 ± 8°). Both the pelvis and thorax segments also rotated towards a more front-on position about the global vertical axis throughout the downswing (Figure 5.3). The angular separation (Z-factor) between these two segments had increased during the early stages of the downswing, reaching a maximum of 15 ± 7° at 0.089 ± 0.047 s before impact, around the time of ball bounce. The angular rotation of the thorax about the global vertical axis then sped up, causing the Z-factor to reduce to 6 ± 8° at impact. At the time of impact both the pelvis (-31 ± 10°) and thorax (-37 ± 11°) had reached a relatively front-on position (Figure 5.3) from which to impact the ball.

In order to generate the downswing motion of the bat, both the front (39 ± 13°) and back (70 ± 13°) shoulders both exhibited large amounts of flexion, which in combination with the more front-on position of the thorax segment created the majority of the motion of the upper arm segments towards the ball. The front shoulder was also found to abduct away from the thorax segment during the downswing (15 ± 11°) and internally rotate (-20 ± 12°), while the back shoulder adducted towards the thorax by 14 ± 9° while externally rotating (46 ± 12°) to bring the bat into line with the ball. Both the front (11 ± 16°) and back (42 ± 12°) elbows were found to extend during the downswing, reaching 124 ± 17° and 102 ± 11° respectively at the time of impact. Similarly, the angle formed between the bat and the top forearm relating to the cocking of the wrists, decreased to 110 ± 8° during the early stages of the downswing, before releasing to reach 145 ± 12° at the time of impact.

Some evidence of the sequential peaking of segment velocities in a proximal to distal order was also found (Table 5.1), suggesting the use of a kinetic chain in order to generate bat speed in the downswing. The resultant forwards velocity of the whole body centre of mass is found to peak first, followed by the transverse rotation of the pelvis and thorax segments, then the back elbow and wrist joint centres in turn, before finally the peaking of the bat resultant distal endpoint speed just before the time of impact (Figure 5.7). This sequential peaking of velocities is also clearly displayed via a single representative trial, showing the increasing sequential velocities in the transverse rotation of the pelvis and thorax segments (Figure 5.8), and in the distal endpoint speeds of the back arm and bat segments (Figure 5.9). This finding is in agreement with the study of Stretch et al. (1998), who suggested batsmen utilised a kinetic chain to generate bat speed in the forward drive. While a sequencing of peak velocities is found in the trunk and back arm, no such sequencing is found in the front arm during the hitting action. Front arm peak speeds were instead found to occur around the same time as those of the pelvis and thorax segments. In its entirety, this perhaps gives support to the suggestion of coaching literature (MCC, 1987; Woolmer, 2008) that the top hand is responsible for controlling the direction of the bat, while the bottom hand reinforces around the time of impact.

Table 5.1: Maximal segment angular velocities and resultant distal endpoint speeds in the forward drive, and the time each occurred in relation to impact for all trials (n = 276) (mean ± SD).

Variable	Velocity	Time (s)
COM	1.21 ± 0.36 ms^{-1}	-0.088 ± 0.034
Pelvis X	-199 ± 62°s^{-1}	-0.064 ± 0.027
Pelvis Z	261 ± 93°s^{-1}	-0.077 ± 0.026
Thorax X	-385 ± 172°s^{-1}	-0.063 ± 0.017
Thorax Z	434 ± 175°s^{-1}	-0.063 ± 0.019
Front elbow JC	4.09 ± 0.64 ms^{-1}	-0.066 ± 0.019
Back elbow JC	5.48 ± 0.66 ms^{-1}	-0.045 ± 0.016
Front wrist JC	5.39 ± 0.74 ms^{-1}	-0.067 ± 0.011
Back wrist JC	5.57 ± 0.56 ms^{-1}	-0.036 ± 0.018
Bat	19.16 ± 1.75 ms^{-1}	-0.018 ± 0.004

Note: COM = centre of mass, rotations in X correspond to anterior/posterior rotation or flexion/extension, rotations in Z correspond to transverse rotation, JC = joint centre, negative timings represent time before impact.

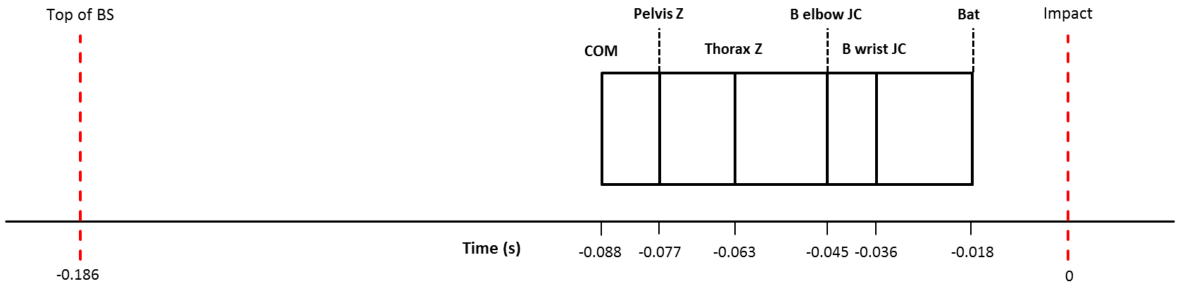


Figure 5.7: The timing of maximal segment angular velocities and resultant distal endpoint speeds in the forward drive.

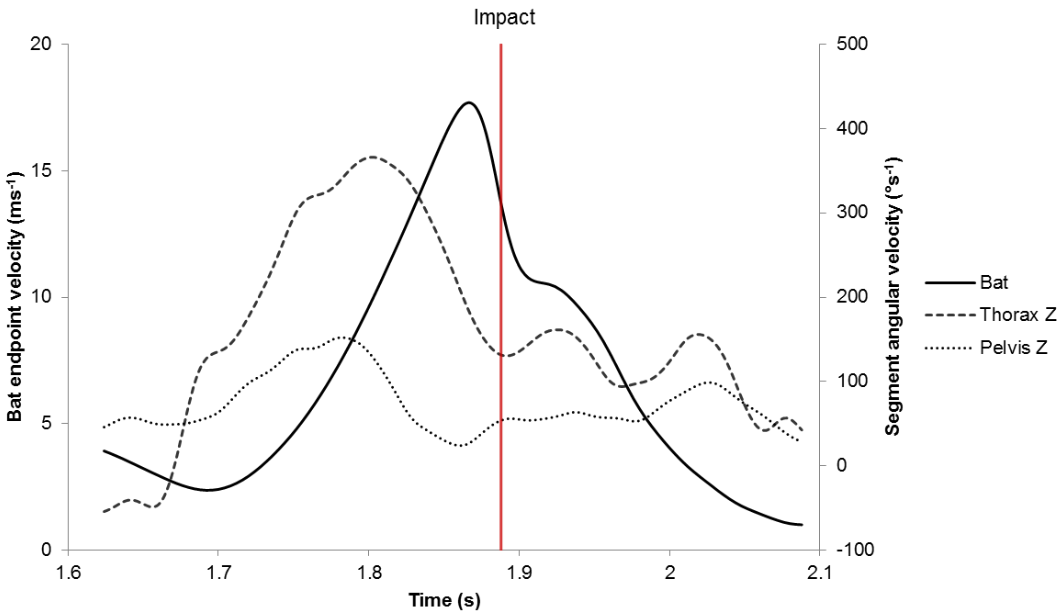


Figure 5.8: Angular velocities (in the transverse plane) of the pelvis and thorax and resultant distal endpoint speed of the bat in the downswing for a single representative trial.

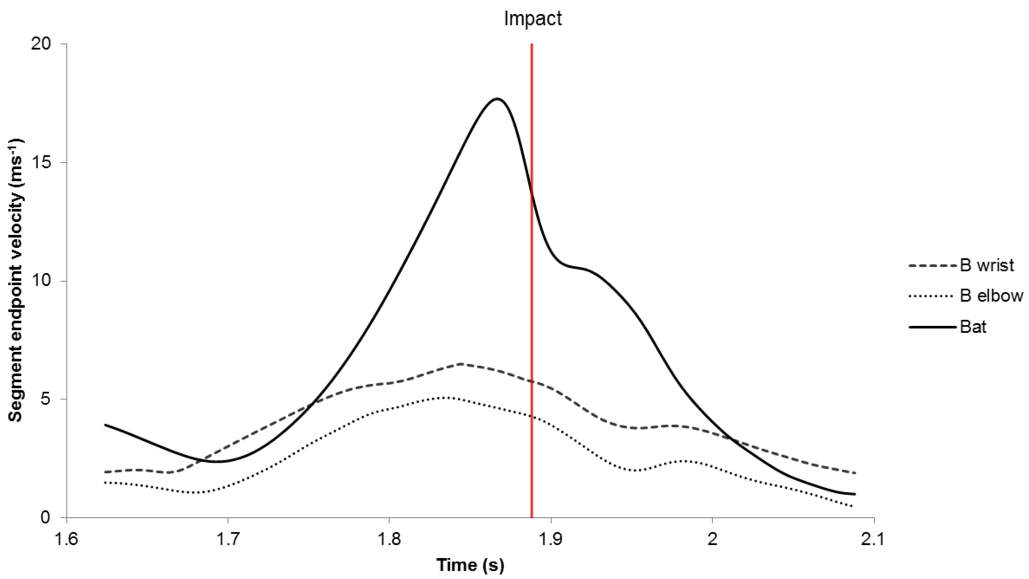


Figure 5.9: Resultant distal endpoint speeds of the back upper limb and bat in the downswing for a single representative trial.

At the point of impact both the front (152 ± 14°) and back (152 ± 15°) knees were found to be moderately flexed. While these values are very similar to those found at the end of the front foot stride, the increased variability in the front knee angle suggests that some adjustment is being made at this late stage of the shot. Both hips were found to extend in the phase between the end of the front foot stride and impact, reaching 124 ± 11° and 180 ± 10° for the front and back hips respectively. The centre of mass was positioned considerably forward of centre relative to the base of support, at 68 ± 7% of the distance from the back to front foot. This indicates that it had moved forwards a further 5% (0.054 ± 0.047 m) relative to its position at the end of the front foot stride. This apparent forwards movement of the body's centre of mass can be explained by the shortening of the base of support at the point of impact when compared to the end of the front foot stride (0.844 ± 0.113 m compared to 0.867 ± 0.114 m), largely caused by forward motion of the back foot (0.027 ± 0.038 m), and by the positioning of the arms and bat in a more advanced position as impact occurs.

At the moment of impact, the front knee joint centre (-0.078 ± 0.043 m), shoulder joint centre (-0.173 ± 0.112 m), and a point between the eyes (-0.081 ± 0.123 m) were all positioned backward of the front foot in the global anterior-posterior plane. While the front knee and shoulder were in similar positions relative to the front foot at the end of the front foot stride, the head had moved forward (0.027 ± 0.042 m) towards the ball in this pre-impact phase. This supports the findings of Stretch et al. (1998) who discovered that players dipped their heads forwards in the approach to impact in order to maintain the transfer of weight into the ball. The bat centre of mass (as an alternative to ball centre position which was not available for all trials) was found to be marginally ahead of the front knee (0.035 ± 0.146 m) and point between the eyes (0.063 ± 0.103 m) in the global anterior-posterior plane at the point of impact. The large variability in these measures indicates that, while the mean of these impacts may occur approximately under the eyes as recommended in coaching literature (ECB, 2009), substantial differences in the impact location relative to the position of the head and front knee are present across the range of trials in this study.

5.2.7 The Follow Through

The follow through occurs following the bat-ball impact, and involves the batsman slowing their limbs and the bat down to a stop at the end of the batting shot. All batsmen tested favoured the checked follow through, with only 31 out of 276 forward drive trials displaying a full follow through. Post-impact bat speed was not investigated here, as it has no direct bearing on the outcome of the batting shot, although Stretch et al. (1998) found the bat to retain approximately 95% of its pre-impact speed after impact with the ball.

5.2.8 Outcome

Although post-impact ball speed could not be measured for all bowling machine trials due to issues with the reflective tape in the first testing session, the mean resultant post-impact ball speed from the remaining 168 trials (18 subjects) was 19.0 ± 3.4 ms^{-1}. This provides a useful measure of shot outcome, and a means for comparison with other shot types investigated here.

5.2.9 Questions from the Data

In this section a series of questions are addressed either comparing findings from this study to previous research or coaching literature, or simply investigating relationships between variables within the data set. All statistical analyses were conducted within Statistical package for the Social Sciences (SPSS) v.22 (SPSS Corporation, USA). All correlation tests were Pearson product-moment correlations, and all t-tests performed were independent samples t-tests. All interval data throughout these analyses was checked for normality using a Kolmogorov-Smirnov test before statistical analysis was conducted, and the assumption homogeneity of variance between group data in each independent samples t-test was confirmed to be non-significant using Levene's test.

1. Is there evidence of a coupling between the initiation of backswing and stride events?

Although the start of the backswing and forward stride events were found to be significantly different to each other ($t_{(264)} = 5.124$, $p < 0.01$) they were also strongly correlated ($r = 0.54$, $p < 0.001$), indicating some coupling of the two as in the studies of Renshaw et al. (2007) and Pinder et al. (2009; 2011a).

2. Is the start of the bat downswing coupled to the completion of the forward stride?

Contrary to the studies of Weissensteiner et al. (2011) and Sarpeshkar et al. (2015), the timing of the end of the forward stride and initiation of the downswing events were significantly different in this case ($t_{(264)} = 35.004$, $p < 0.001$), perhaps as suggested by Stuelcken et al. (2005) because of the increased temporal constraints placed on the batsman by the increased ball speed. It is suggested that, although the end of the forward stride and ball bounce events were again found to be significantly different ($t_{(264)} = 6.738$, $p < 0.001$), the small mean timing difference between these events (0.023 ± 0.056 s) represents a stronger potential coupling than between the end of the forward stride and commencement of the downswing events.

3. *Is the head position of the left handed batsmen different to the right handed batsmen at the point of ball release?*

The head position of the left handed batsmen (mean = 0.004 ± 0.051 m outside the line of middle stump) was found to significantly differ ($t_{(274)} = -9.566$, $p < 0.001$) from the head position of the right handed batsmen (mean = 0.095 ± 0.085 m outside the line of middle stump) at the point of ball release. This suggests that while left handed batsmen preferred to align their eyes with middle stump during their setup, right handed batsmen chose to position themselves further across towards the off stump. This could be explained by the positioning of the bowling machine such that it emulated a right-arm over delivery, creating a different angle for the left handed batsmen to contend with compared to the right handers.

4. *Is there a relationship between line and length of the delivery and the magnitude of the stride used by players in the forward drive?*

Interestingly, players in general were found to exhibit a longer stride when hitting deliveries wider of off stump ($r = 0.433$, $p < 0.001$; as recommended by MCC (1987) and found by Elliott et al. (1993)) and deliveries arriving at the batsman higher above the ground (assumed to indicate a shorter length; $r = 0.250$, $p < 0.01$). This is likely attributable to batsmen trying to get closer to the pitch of the ball in order to minimise the potential for deviation between the times of ball bounce and impact.

5. *Are the maximum bat angular velocity and resultant distal endpoint speed in the downswing correlated?*

The maximum bat angular velocity and resultant distal endpoint speed in the downswing were found to be strongly correlated ($r = 0.875$, $p < 0.001$). Although this indicates a very strong relationship, it also shows that bat motion in the forward drive is not purely rotational, and that players vary the rotational and translational components of the bat swing from shot to shot.

6. *Is there a relationship between the type of follow through used (full or checked) and the line of the delivery or the maximum pre-impact bat speed?*

The use of a full follow through was strongly correlated with batsmen reaching for deliveries wider of off stump ($r = -0.524$, $p < 0.001$). Maximum bat linear distal endpoint speed was also found to be significantly different between the two types of follow through (mean 20.94

± 1.79 for a full follow through compared to 18.94 ± 1.61 for a checked follow through; $t_{(274)} = 6.452$, $p < 0.001$). Interestingly, bat linear distal endpoint speed was also moderately correlated with the line of the delivery ($r = 0.323$, $p < 0.001$), suggesting that maximum bat speed tends to be higher for deliveries wider of off stump. This indicates that players may realise that on occasions where their bat speed is higher, they need longer to slow the swing down, and therefore opt to use a full follow through.

5.3 The Pull Shot

The pull shot can also be considered to consist of five phases: the stance, backswing, foot movement/weight transfer, downswing to impact, and follow through (Figure 5.10). These phases were defined via a series of events described in section 4.5.2.2. As with the forward drive, in many situations these phases in fact occur simultaneously or overlap in their timings. The techniques used by the 27 batsmen who played pull shots (n = 9.8 ± 1.5) against the bowling machine during this study are described. Typical delivery characteristics for this set of pulls are also reported. There are substantially fewer previous studies and coaching recommendations regarding the pull shot when compared to the forward drive, as such comparisons to previous work in this section proved more difficult.

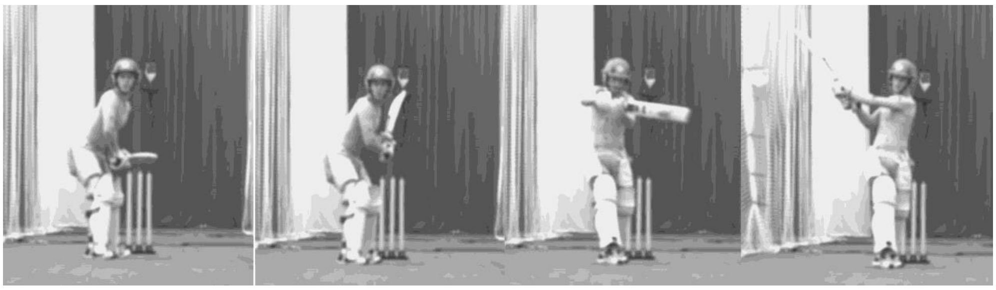


Figure 5.10: The pull shot - (A) stance phase; (B) backswing and foot movement/weight transfer phase; (C) downswing to impact; (D) follow through.

5.3.1 Delivery Characteristics

At the time of release, ball speed from the bowling machine as measured by the Trackman unit ranged from 72.8 – 81.5 mph (mean = 77.9 ± 3.6 mph), or 32.5 – 36.4 ms^{-1} (mean = 34.8 ± 1.6 ms^{-1}). Due to logistical issues and occasional errors in the tracking of the device, these values represent the measured ball speeds from 16 of the 29 players tested. Again, this speed does not represent truly fast bowling at an international level, although is representative of the speeds used in training by the set of players tested, and was deemed appropriate by an ECB level 4 elite international coach.

The ball release to impact time as calculated from the high-speed video and motion capture data was 0.531 – 0.657 s (mean = 0.594 ± 0.047 s). Ball bounce was found to occur on average 0.270 ± 0.039 s after ball release, and 0.324 ± 0.035 s before bat-ball impact. This equates to the ball pitching after an average of 45.5% of total ball release to impact time, indicating a consistently short-pitched delivery suitable to play the pull shot. At the point of impact, the ball (averaged across the 159 trials with ball tracking) was positioned on average 0.332 ± 0.181 m outside the line of middle stump towards the off-side, and 1.334 ± 0.196 m above the pitch surface, representing a suitable position to hit a pull shot in front of square on the leg-side.

5.3.2 Movement Timings

The mean timings of each key event across all 27 subjects who hit pull shots against the bowling machine are shown in Figure 5.11. The backswing began 0.156 ± 0.072 s after ball release, indicating a considerably later commencement of the backswing, and thus the batsman's initial movement, than when playing the forward drive. The backswing lasted for an average of 0.230 ± 0.065 s, before again undergoing a fluid transition into the downswing. The timing of backward weight transfer (section 4.5.2.2) occurred on average just after the start of the backswing, beginning 0.183 ± 0.121 s after ball release. However, the relatively large standard deviation in this timing measure displays the wide range of weight transfer techniques used by the range of players tested, with some choosing to begin to shift their weight around the time of ball release, and others waiting until the downswing was underway before moving backwards.

The downswing began on average 0.208 ± 0.029 s before impact, again with the low standard deviation in this measure indicating a remarkably similar downswing time across all players tested. The timing of the point at which the hands switched from moving in a backwards direction to a forward direction ('hands forward DS' event) was found to occur on average marginally before the other definition of the start of the downswing (0.213 ± 0.028 s before impact). These two events were found to often coincide, and as such the 'hands forward DS' event was not included in the timing plot below or later analysis of the pull shot. Due to the range of foot movement techniques applied by batsmen in this study, no objective measures of foot movement timings have been included in this analysis.

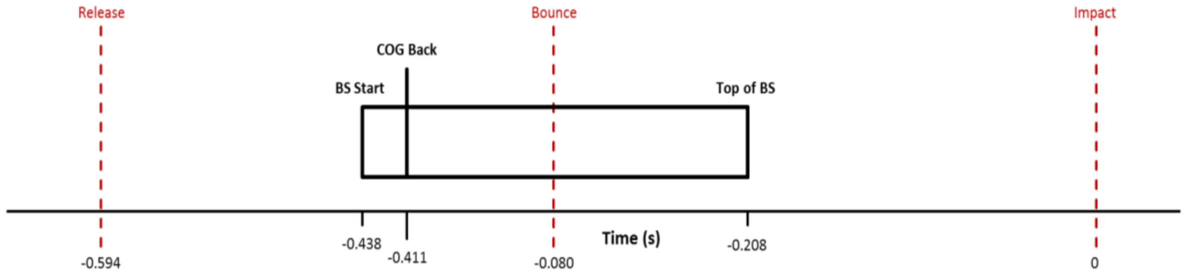


Figure 5.11: Mean timings of key events in the pull shot.

5.3.3 The Stance Phase

Players displayed a mean stance width of 0.529 ± 0.090 m, equating to 171 ± 37% of their shoulder width. This is very similar to the mean stance width used when executing the forward drive, and as such is considerably wider than is recommended by coaching literature (MCC, 1987; ECB, 2009). A subjective analysis of the trigger movements used by players found 18 out of the 27 players tested to exhibit some form of trigger movement, with the remaining nine standing still in the approach to ball release. Of the 18 players who utilised a trigger movement, seven employed a simple forward press, five moved their back foot back before initiating a forward press, four moved both feet back and across towards the off stump prior to ball release, one moved his back foot forward before initiating a forward press, and one moved just his back foot back towards off stump prior to ball release. As with the forward drives, this shows a wide variety of techniques being used by elite batsmen, and a marked increase on the three basic movements outlined by Woolmer (2008).

At the moment of ball release the batsman's centre of mass was positioned forward of centre relative to the base of support, on average at 59 ± 8% of the distance from the front foot to back foot. Consequently, the front shoulder (-0.024 ± 0.068 m), knee (-0.009 ± 0.037 m) and a point between the eyes (-0.037 ± 0.072 m) were all found to be marginally behind the centre of mass of the front foot at the point of ball release. The same point between the eyes was also found to be positioned on average 0.058 ± 0.069 m outside the line of middle stump (towards the off-side) in the global medio lateral plane. The forwards of centre positioning of the centre of mass can again be largely explained by the substantial forwards flexion displayed in the thorax segment (-37 ± 8°), and small amount of lateral flexion towards the bowler (-2 ± 4°). The fact that batsmen still positioned their centre of mass forward of centre at the point of ball release, despite the pre-release knowledge that the ball would be pitched short, works again in supporting the studies of Stretch et al. (1998) and Taliep et al. (2007), who suggested batsmen position their centre of mass forward of centre relative to the base of support in the stance. Further analysis of whether batsmen change their setup position when they are unsure of the pitch length of the approaching delivery will make for an interesting comparison.

Both knees were flexed in the stance, with the front knee exhibiting a greater degree of flexion (141 ± 7°) than the back (145 ± 10°). Both knees underwent a small amount of additional flexion by the time of ball release, reaching 139 ± 7° and 141 ± 9° for the front and back knees respectively. The front (129 ± 12°) and back (138 ± 14°) hips were also flexed in the stance, and as with the knees they experienced further a small amount of further flexion by the time of ball release, flexing to 126 ± 12° and 136 ± 13° respectively. As with the forward drive, this caused a drop in the whole body centre of mass height from 0.987 ± 0.038 m in the stance to 0.972 ± 0.036 m at the point of ball release. The pelvis (-71 ± 7°) and thorax (-70 ± 7°) segments were also similarly aligned about the global vertical axis (Figure 5.3), indicating again that players preferred a slightly open stance at the point of ball release, as in the work of Stuelcken et al. (2005) when assessing the forward drive.

5.3.4 The Backswing

At the start of their backswing, batsmen exhibited a mean bat angle about the global medio-lateral axis (bat angle X) of -110 ± 24° (Figure 5.4), forming an angle with the top forearm (relating to the angle of cocking at the wrists) of 130 ± 14°. This equated to a bat centre of mass height of 0.951 ± 0.150 m above the pitch surface. At this instant the bat was also angled towards the off-side about both the global anterior posterior (-17 ± 11°; bat angle Y – Figure 5.5) and vertical (-30 ± 18°; bat angle Z – Figure 5.6) axes. The top and bottom wrist joint centres were positioned 0.889 ± 0.061 m and 0.966 ± 0.084 m above the pitch surface respectively.

During the backswing, the thorax extended from -39 ± 8° at the start of the backswing to -31 ± 7° at the top of the backswing in preparation for a short pitched delivery. Similarly, the pelvis displayed a small amount of posterior rotation from -25 ± 9° at the start of the backswing to -18 ± 8° at the top of the backswing. The bat was raised to an angle of -152 ± 15° about the global medio-lateral axis at the top of the backswing (Figure 5.4), raising the bat centre of mass to 1.371 ± 0.103 m above the pitch surface. The bat also displayed an increased angle towards the off-side about the global vertical axis (-72 ± 17°; Figure 5.6), indicating a very open bat face at this point. The bat angle about the global anterior-posterior axis (Figure 5.5) was found to decrease to a minimum of -19 ± 12°, indicating an angling towards the off-side, before straightening up and reaching 11 ± 13° at the top of the backswing, indicating an angling towards the leg-side. This again suggests a distinctly looped bat path in the transition from backswing to downswing, as found by Stuelcken et al. (2005) in the forward drive.

In order to create the backswing movement, batsmen exhibited flexion (16 ± 9° and 9 ± 14°), adduction (-28 ± 12° and -10 ± 9°), and internal rotation (-4 ± 9° and -21 ± 11°) at both the front and back shoulders respectively. The front elbow was found to extend marginally between the start and end of the backswing (111 ± 15° to 113 ± 12°), while the back elbow displayed substantial flexion (79 ± 13° to 55 ± 9°). This caused the wrist joint centres to move an average of 0.195 ± 0.080 m towards the off-side away from the batsman's body in the global medio-lateral plane, -0.166 ± 0.088 m backwards in the global anterior-posterior plane, and 0.212 ± 0.092 m up in the global vertical plane. The angle of wrist cocking formed between the bat and top forearm also decreased by 10°, reaching 120 ± 11° at the top of the backswing. This suggests that, as opposed to in the forward drive where players seem to use a largely levered backswing, when executing the pull shot, batsmen prefer to move their hands and arms backwards and up, as well as generating a cocking motion at the wrists and elbows, before executing the downswing.

At the top of the backswing, the pelvis segment had begun to rotate anticlockwise about the global vertical axis (Figure 5.6), reaching a more front-on angle of -61 ± 7°. Meanwhile the thorax remained in a more side-on position (-70 ± 7°) at the top of the backswing, generating an angular separation between lines defining the medio-lateral planes of the pelvis and thorax segment (Z-factor) of 8 ± 5°. An angular separation between the pelvis and thorax segments (12 ± 10°) was also found in the frontal plane (X-factor) at the top of the backswing, with the thorax displaying greater forwards flexion (-31 ± 7°) than the pelvis segment (-18 ± 8°).

5.3.5 Foot Movement/Weight Transfer Phase

Unlike the forward drive where all players exhibited a forward stride before impact, investigation of the range of pull shot techniques used by batsmen tested in this study found a variety of foot movement patterns. While the foot movement patterns exhibited by batsmen was difficult to identify and quantify automatically, a subjective analysis showed thirteen players to move their back foot back then swivel on it during and after the downswing, while six swivelled on the back foot with no backwards movement, four stood still to hit, two moved their back foot back and hit without swivelling, one moved their back foot back and jumped during the downswing, and one stepped forward into the ball. Although a number of players moved backwards with their back foot as recommended by coaching literature (MCC, 1987; Woolmer, 2008; ECB, 2009) this shows that not all players utilise this movement pattern. Investigation of the foot movement patterns when facing different delivery methods particularly when the ball length is unknown will prove interesting in this case.

During the weight transfer phase, the batsman's centre of mass travelled on average -0.160 ± 0.073 m backwards in the global anterior-posterior plane, while also raising 0.151 ± 0.062 m in the global vertical plane. This was caused largely by substantial extension at the front (27 ± 14°) and back (17± 13°) knees, and front (19 ± 10°) and back (44 ± 11°) hips in the time between the start of weight transfer and ball impact. The thorax segment was also found to display considerable extension during the weight transfer phase, extending from a relatively flexed position (-37 ± 9°) to an upright position (4 ± 7°) at impact. In combination with the extension at the knees and hips, this caused the head to move on average -0.289 ± 0.102 m backwards in the global anterior-posterior plane, and 0.162 ± 0.090 m up in the global vertical plane during this phase of movement.

5.3.6 The Downswing to Impact

During the downswing the bat reached a maximum angular velocity about the global medio-lateral axis (corresponding to the main axis the bat swing) of 1796 ± 312°s^{-1}, equating to a maximum resultant linear distal endpoint speed of 21.71 ± 2.01 ms^{-1}, and reaching an angle about the global medio-lateral axis (bat angle X) of 72.7 ± 21.2° (Figure 5.12). Although it is unlikely the motion of the bat is purely rotational, separation of the rotational and translational components was found to be difficult and unnecessary for this analysis due to the presence of a resultant endpoint speed. The angular separation between the pelvis and thorax segments in the transverse plane (Z-factor) increased to a maximum of 10 ± 5° during the downswing 0.163 ± 0.044 s before impact. The angular rotation of the thorax then sped up relative to the pelvis, reducing the angular separation which reached -9 ± 7° at the point of impact, indicating the thorax (4 ± 9°) was in a more front-on position at this time than the pelvis (-5 ± 11°; Figure 5.3). The angular separation between the pelvis and thorax segments in the frontal plane (X-factor) also increased to a maximum of 13 ± 10° during the downswing 0.198 ± 0.039 s before impact. Again this angular separation reduced in the approach to impact, reaching -7 ± 8° at the point of impact, indicating the thorax was rotated further backwards at this time than the pelvis segment.

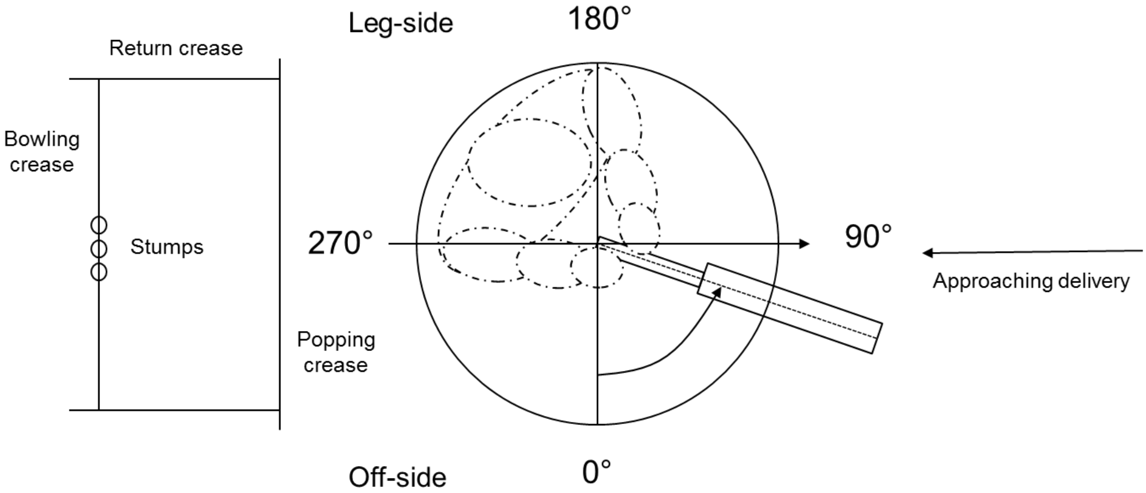


Figure 5.12: Bat angle X – bat angle about the global medio-lateral axis in the downswing of the pull shot.

In order to generate the downswing motion of the bat, both the front and back shoulders exhibited flexion (front 15 ± 13°; back 58 ± 20°) and abduction (front 21 ± 13°; back 14 ± 13°). While the back shoulder also displayed a substantial amount of external rotation (55 ± 12°), the front shoulder remained at a relatively constant level of rotation, on average rotating internally just -4 ± 11°. Both the front (27 ± 20°) and back (72 ± 19°) elbows were found to extend during the downswing, reaching 140 ± 21 and 127 ± 17° at the time of impact respectively. This considerable extension of the back elbow is recommended by coaching literature (Woolmer, 2008) as helping to generate bat speed and aid in controlling the shot through the time of impact. Similarly, the angle between the top forearm and bat (wrist cocking angle) decreased to a minimum of 104 ± 11° during the downswing, before uncocking to reach 160 ± 11° at the point of impact.

As opposed to in the forward drive where a sequential peaking of segment velocities in a proximal to distal order was found, when playing the pull shot batsmen displayed little evidence of segmental sequencing, suggesting that a kinetic chain was not used in this case to generate bat speed in the downswing (Table 5.2). Although peak pelvis angular velocity was found to occur on average 0.011 s before the thorax, which in turn occurred 0.012 s before the next peak segmental speed (front wrist joint centre), there is no evidence of proximal to distal sequencing in either of the arms, with the upper arm segment speed peaking marginally after the forearm in both cases.

Table 5.2: Maximal segment angular velocities and resultant endpoint speeds for the pull shot, and the time each occurred in relation to impact for all trials (n = 264) (mean ± SD).

Variable	Velocity	Time (s)
COM	-0.77 ± 0.28 ms^{-1}	-0.065 ± 0.052
Pelvis Z	393 ± 68°s^{-1}	-0.096 ± 0.027
Thorax Z	514 ± 83°s^{-1}	-0.085 ± 0.026
Front elbow JC	4.59 ± 0.86 ms^{-1}	-0.064 ± 0.028
Back elbow JC	4.85 ± 0.68 ms^{-1}	-0.066 ± 0.020
Front wrist JC	5.51 ± 0.87 ms^{-1}	-0.073 ± 0.019
Back wrist JC	4.85 ± 0.68 ms^{-1}	-0.066 ± 0.020
Bat	21.71 ± 2.01 ms^{-1}	-0.018 ± 0.005

Note: COM = centre of mass, rotations in Z correspond to transverse rotation, JC = joint centre, negative timings represent time before impact.

At the point of impact, the front knee (165 ± 13°) was found to be more extended than the back knee (151 ± 13°), while the front hip (146 ± 10°) was more flexed than the back hip (180 ± 8°). This extension relative to the start of the downswing caused the whole body centre of mass height to increase substantially compared to its starting position, reaching 1.119 ± 0.046 m at the point of impact. The centre of mass was also positioned backwards of centre relative to the base of support at the moment of impact, at 41% of the distance from back to front foot. Consequently, a point between the eyes was considerably backwards of the centre of mass of the front foot (-0.288 ± 0.110 m) at this time. This indicates that, as opposed to the forward drive where the batsman's weight was constantly being transferred forwards towards the ball, in the pull shot batsmen transfer their weight backwards and maintain that position in the approach to impact. Interestingly, this is contrary to the recommendations of current coaching literature (Woolmer, 2008; ECB, 2009), who suggest the weight should be positioned forward of centre throughout the downswing motion.

At the point of impact, the bat centre of mass (as an alternative to ball centre position which was not available for all trials) was positioned 0.588 ± 0.110 m ahead of a point between the eyes in the global anterior-posterior plane. This is in line with coaching literature (MCC, 1987; Woolmer, 2008; ECB, 2009), which suggests impact should occur far out in front of the head, with the arms as extended as possible. However, the bat centre of mass was also found to be positioned 0.286 ± 0.131 m outside the line (towards the off-side) of the same point between the eyes, suggesting impact occurred on average substantially away from the line of the head. This is against the recommendations of coaching literature, which suggests that players should move across such that impact occurs as near as possible to the line of the head (MCC, 1987), or just outside to avoid injury if the ball is missed (Woolmer, 2008).

5.3.7 The Follow Through

The majority of batsmen were found to swivel on their back foot during their follow through, allowing a more natural and gradual slowing down of the body and bat after the effort put into the downswing, resulting in a bat angle about the global medio-lateral axis (corresponding to the main axis of the swing) of 162.6 ± 27.3° at the end of the follow through (Figure 5.12).

5.3.8 Outcome

Although post-impact ball speed could not be measured for all bowling machine trials due to issues with the reflective tape in the first testing session, the mean resultant post-impact ball speed from the remaining 159 trials (17 subjects) was 21.41 ± 3.96 ms^{-1}. This again provides a useful measure of shot outcome, and a means for comparison with other shot type investigated in this study.

5.3.9 Questions from the Data

In this section a series of questions are addressed comparing findings from this study to coaching literature, investigating relationships between variables within the data set, or differences between certain aspects of the forward drive and pull shot techniques used. Again all statistical analyses were conducted within SPSS v.22 (SPSS Corporation, USA). All correlation tests were Pearson product-moment correlations, and all t-tests performed were paired samples t-tests unless otherwise stated. All interval data throughout these analyses was checked for normality using a Kolmogorov-Smirnov test before statistical analysis was conducted, and the assumption homogeneity of variance between group data in each independent samples t-test was confirmed to be non-significant using Levene’s test.

1. *Is the head position of the left handed batsmen different to the right handed batsmen at the point of ball release?*

An independent samples t-test found the head position of the left handed batsmen (0.011 ± 0.031 m outside the line of middle stump) to significantly differ ($t_{(262)} = -8.362$, $p < 0.001$) from the head position of the right handed batsmen (0.080 ± 0.071 m outside the line of middle stump) at the point of ball release. This suggests, as in the forward drive that left handed batsmen preferred to stay more towards middle stump in their alignment, as opposed to right handed batsmen who positioned themselves more towards off stump. Again, this could be explained by the positioning of the bowling machine such that it emulated a right-arm over bowler, creating a different angle for the left handed batsmen to contend with.

2. *Does the initial movement of the batsmen (either backswing or forward stride/weight transfer) occur at a different time in the forward drive than the pull shot?*

No significant differences ($t_{(25)} = -1.206$, $p > 0.05$) were found between the movement initiation time displayed by batsmen in the forward drive (mean = 0.106 ± 0.062 s) and the pull shot (mean = 0.120 ± 0.065 s).

3. *Is the whole body centre of mass position at the point of ball release different between the pull shot and the forward drive?*

The whole body centre of mass position was found to be significantly further forward ($t_{(26)} = 4.438$, $p < 0.001$) at the moment of ball release when playing the forward drive (mean = 63 ± 9% of the distance from back to front foot) compared to the pull shot (mean = 59 ± 8%). This suggests that due to their pre-release knowledge of ball length, players tend to bias their weight further forwards towards the front foot at the point of ball release when executing a forward drive than when playing a pull shot, although the mean values and small mean difference indicates that players bias their weight forward against the bowling machine irrelevant of whether they are playing a forward drive or pull shot.

4. *Is the backswing height (in terms of bat angle X, bat centre of mass height, and wrist joint centre height at the top of the backswing) different between the pull shot and the forward drive?*

Although no significant differences were found in bat angle (X) at the top of the backswing ($t_{(26)} = 0.754$, $p > 0.05$; mean drive = -149 ± 13°, mean pull = -152 ± 15°), the bat centre of mass position was found to be significantly higher ($t_{(26)} = -14.727$, $p < 0.001$) in the pull shot (mean = 1.371 ± 0.103 m above the pitch surface) than the forward drive (mean = 1.128 ± 0.094 m above the pitch surface). Both the top ($t_{(26)} = -17.535$, $p < 0.001$) and bottom ($t_{(26)} = -11.993$, $p < 0.001$) wrist joint centres were also found to be significantly higher at the top of the backswing in the pull shot (mean top wrist height = 1.104 ± 0.082 m, bottom = 1.175 ± 0.074 m) than in the forward drive (mean top wrist height = 0.869 ± 0.063 m, bottom = 1.032 ± 0.077 m). This indicates that by the top of the backswing players had recognised the ball was pitched short and was on course to arrive considerably above waist height, thus had increased the height of their hands and bat in order to account for this during the bat swing, and attempt to continue to hit down on the ball. Interestingly, the lack of difference in the peak bat angle (X) at the top of the backswing suggests that no additional cocking of the wrists and elbows occurred during this phase, in favour of simply raising the hands and bat further above the pitch surface in preparation for the downswing.

5. *Are the maximum bat angular velocity and resultant distal endpoint speed in the downswing correlated?*

The maximum bat angular velocity and resultant distal endpoint speed were found to be strongly correlated ($r = 0.682$, $p < 0.001$). Despite this showing a strong relationship, it was found to be substantially weaker than in the forward drive, again showing that batsmen alter the rotational and translational components of the bat swing from shot to shot.

6. *Are the maximum pre-impact bat distal endpoint and post-impact ball speeds different between the forward drive and pull shots?*

Both the maximum pre-impact bat distal endpoint ($t_{(26)} = -6.820$, $p < 0.001$) and post-impact ball ($t_{(16)} = -4.247$, $p < 0.01$) speeds were found to be significantly higher for the pull shots (mean bat speed = 21.71 ± 2.01 ms^{-1}; mean ball speed = 21.41 ± 3.96 ms^{-1}) than the forward drives (mean bat speed = 19.16 ± 1.75 ms^{-1}; mean ball speed = 19.01 ± 3.45 ms^{-1}). This suggests that the pull shot technique either allows for or requires a higher speed bat swing in order for successful execution, while perhaps players focus more on generating a good impact location than high bat speed in the forward drive.

5.4 Conclusions and Application to Coaching

This study has provided a thorough description of the kinematics of the forward drive and pull shots as played by the players in this study, answered a series of questions from the data, and effectively introduced many of the variables to be used throughout the remainder of this research. This work has a number of potential applications for both future research and coaching. Initially, the data presented here can now act as a comparison for future studies investigating the kinematics of the forward drive and pull shots, and a basis for the assessment of new methodologies or individual player assessments. The sheer wealth of data, along with the series of questions posed at the end of each section, highlights a vast number of possible future directions for researchers to investigate, and provides data to support or question their claims. Although all the data presented here was captured while batting against a bowling machine, and therefore suffers from a lack of realism to match conditions and truly representative batsman response (Chapter 8), the bowling machine remains a key part of batting training and research due to the control it provides, and as such findings while batting against it are useful in a number of ways, and generally represent the key techniques displayed by the batsmen in this study over a large number of trials.

The wealth of data available could prove of use to coaches in developing the techniques of young batsmen through comparison against current elite players. For example, the coupling of movements to each other (the commencement of the backswing and forward stride events) and to the delivery (the completion of the forward stride and ball bounce events) provide a focus for players generating efficient and fluid movements in the forward drive. The relationship found between the line of the ball and stride length during the forward drive adds weight to existing coaching practice, and provides evidence of best practice employed by elite batsmen. Future studies should focus on further relationships between ball delivery (line, length, and speed) and shot kinematics, such that the depth of technical coaching recommendations can be increased and additional knowledge gained. Finally, findings comparing backswing techniques found the bat centre of mass and wrist joint centres to be significantly higher at the top of the backswing in the pull shot than the forward drive, although no differences were found in terms of bat angle. The high levels of wrist cocking found during both shots suggests this backswing technique is important for efficient bat speed generation and shot execution, thus should be taught by coaches to young cricketers.

Although the data presented in this study provides a detailed examination of the forward drive and pull shots as played by a range of batsmen, further interrogation of the data may offer additional information. The large variability found in certain variables highlights the different kinematic approaches exhibited by some batsmen. A case study approach considering a single subject or small group may extract more useful information, particularly when considering the truly elite international batsmen. This not only allows researchers and coaches the opportunity to examine in detail the techniques of some of the best players in the world, and provide up-to-date coaching recommendations based on this knowledge, but also to track their development and any technical changes over time, and assess the within subject variability exhibited by these players. This may go further in revealing commonalities and differences between truly elite batsmen, and begin to extract the features of technique critical to success.

5.5 Chapter Summary

This chapter has provided an overview of the components of both the forward drive and pull shots, and described the techniques and kinematics adopted by the subjects tested in this study. A number of questions, based on relationships discussed in previous literature, or from detailed examination of the data, were also addressed, and a series of conclusions and recommendations for coaching made.

CHAPTER 6

DETERMINING IMPACT LOCATION AND ITS EFFECTS ON SHOT OUTCOME

6.1 Chapter Outline

This chapter outlines a methodology for the accurate determination of the impact location of a cricket ball on the bat face using three-dimensional motion capture data, as well as the identification of bat-ball contact timing and post-impact instantaneous ball speed. It then details a series of checks to validate the accuracy of each stage of the methodology, and assess its applicability to larger data sets. Finally, the effects of impact location on shot outcome, in terms of resulting post-impact bat twist, ball speed, and ball direction are investigated via a series of range hitting trials.

6.2 Introduction

In cricket, the impact location of the ball on the bat face has a considerable effect on the subsequent post-impact ball trajectory, with impacts further from the defined sweetspot of the bat (in this case the point of impact resulting in the highest ball rebound speeds) resulting in lower ball speeds (Bower, 2012), and often causing the bat to twist and the ball to depart on unintended trajectories (Symes, 2006). Evidently the impact location has a substantial influence on the outcome of the batting stroke, and thus is an important measure of success in cricket batting. Despite this, there has been minimal research investigating methods for determining an accurate measure of ball impact location during a dynamic hitting motion.

Attempting to obtain an accurate measure of ball impact location on the face of a cricket bat presents the researcher with a number of challenges. Ball release speeds between 32.0 and 40.0 ms^{-1} are common for international fast bowlers (Worthington et al., 2013), and while the ball slows down during its flight and contact with the pitch, it can still be expected to reach the batsman with 82 to 86% of its initial speed (32.8 - 34.4 ms^{-1} for a 40.0 ms^{-1} delivery; James et al., 2004). Due to this high ball speed, along with short impact durations around 1.0 – 1.5 ms (Symes, 2006), and the relatively low capture rates used in typical human motion capture studies (250 Hz – 300 Hz; Peploe et al., 2014; Worthington et al., 2013), the exact time of impact is often missed by the motion capture system. These difficulties in ascertaining impact timing, as well as rapid marker movement and tracking errors caused by spin on the ball, make determination of the impact location of the ball on the bat face problematic. As a consequence of this, many existing biomechanical studies disregard impact location as a measure of success, often focussing on pre-impact bat and post-impact ball speed instead (Elliott et al., 1993; Stretch et al., 1998; Stuelcken et al., 2005; Taliep et al., 2007; Cork et al., 2010), or use a simple categorical measure of the quality of bat-ball contact based on a scale from 0 to 2 (Muller and Abernethy, 2006; section 2.8.1.7). This decreases their ability to determine or accurately speculate on the factors affecting batting success. A number of researchers have measured impact location in a sports setting, although methods used are often time consuming, lacking in accuracy and validation, or inappropriate for a cricket application (section 2.8.1.7).

This chapter aimed to develop and validate a methodology for accurate determination of bat-ball impact location, as well as the timing of impact and instantaneous post-impact ball speed, using motion capture data in a whole body data capture environment. This will also allow for more accurate assessment of joint and bat kinematics at the instant of bat-ball impact, as well as the post-impact ball trajectory, and provides a methodology to assess individual shot outcome in later studies. Finally, this chapter will investigate the effects of impact location on shot outcome in terms of post-impact bat and ball motion via a series of range hitting trials, in order to assess the margin for error afforded to a batsman when hitting in these circumstances.

6.3 Methodology

All testing was carried out at England & Wales Cricket Board National Cricket Performance Centre in Loughborough, UK, on the same artificial pitch surface as player testing. Data was recorded using an 18 camera Vicon Motion Analysis System operating at 250 Hz as outlined in section 3.7.

6.3.1 Stage 1 – Spatial Reconstruction Accuracy

Following camera calibration (section 4.2.1), the 3D spatial reconstruction accuracy of the motion capture system was determined. This was achieved by passing an array of markers with fixed separation through the capture volume and measuring the recorded distance between each pair of markers (section 4.2.2). The root mean square error (RMSE) from the mean separation was calculated for each pair as a measure of system noise, and compared to errors found later in the methodology.

6.3.2 Stage 2 – Ball Flight Tracking

6.3.2.1 Data Collection

Five 15 x 15 mm squares of Scotchlite 7610 reflective tape (3M, Bracknell, UK) were attached to a standard size adult cricket ball (Dukes Special County; Figure 6.1). Six 25 mm spherical reflective markers were also positioned on the stumps at the batsman's end of the pitch. Finally, a rigid foam mat with impact paper taped to the front surface was positioned upright directly adjacent to the stumps. Nine trials were then completed consisting of the ball being fired from a bowling machine (BOLA Professional), bouncing on the pitch, and impacting the mat placed adjacent to the stumps with a speed (calculated using differentiated ball position data over a 40 ms time interval) of 22.6 ± 1.1 ms^{-1}.

Figure 6.1: Reflective tape positioned on the cricket ball.

6.3.2.2 Data Reduction

The ball and stumps marker position data were manually labelled and processed, and ball centre position was calculated on a frame-by-frame basis (section 4.3). Gaps in the ball centre position data at any given frame were then manually interpolated using a quintic spline tool in Vicon Nexus software. Curves were fitted to the raw unfiltered ball centre coordinate data for all points occurring after ball bounce (identified from a change in the vertical direction of the ball) and before impact with the mat (identified manually), separately against time in the vertical, anterior-posterior, and medio-lateral planes according to Eq. (1). This equation, based on fundamental mechanical principles, provides more a more valid estimation of actual ball trajectories than straight lines or standard polynomials, thus was chosen for this application. Ground contact was not included in the time period for which curves were fit to the ball coordinate data, so any deceleration was due to air resistance acting on the ball. Eq (1) was therefore derived from knowledge that the drag force acting on a body is proportional to the squared velocity of that body, and additionally that the deceleration of a body is proportional to the force acting on it (Appendix 3):

$$x = \frac{1}{k} \cdot \ln(1 + k \cdot v_0 \cdot t), \qquad (1)$$

Where x = displacement; t = time; and k and v_0 are constants.

Curves were fitted in MATLAB (Version 8.0, The MathWorks Inc., Natick, MA, 2012) utilising a Trust-Region-Reflective Least Squares algorithm (Moré & Sorensen, 1983) to determine values for k and v_0. R^2 and RMSE values, calculated from the difference at each time point, assessed the goodness of fit of the curves to the raw ball centre coordinate data in each plane. Time of impact was estimated as the time at which the pre-impact anterior-posterior curve, plotted against time, intersected with the plane of the mat (taken as the mean anterior-posterior position of the six stump markers). Finally, the estimated ball position at this time in the vertical and medio-lateral planes, calculated from the curve equations, was compared to the measured impact location from the impact paper, and the absolute discrepancy between the two measures was evaluated.

6.3.3 Stage 3 – Impact Location Calculation: Static Ball

6.3.3.1 Data Collection

Five 15 x 15 mm squares of Scotchlite 7610 reflective tape were attached to a standard size adult cricket ball (Figure 6.1). Four 14 mm spherical reflective markers were positioned on the back corners of the blade of a short-handle adult cricket bat (Kookaburra Kahuna 1000; Figure 6.2). A single subject (age 26 years, height 1.88 m, mass 93.2 kg) of premier league club standard performed eight batting shots (four forward drives, four pull shots) hitting a ball suitably positioned on a batting tee. Impact location in each case was recorded using developer spray on the bat face (Figure 6.3) and digitised using Image-Pro Analyser software (Media Cybernetics Inc.).

Figure 6.2: Reflective marker placement on the blade of the cricket bat.

Figure 6.3: Impact location measurement using developer spray.

6.3.3.2 Data Reduction

The ball and bat marker position data were manually labelled and processed, and ball centre position was calculated and interpolated as before (section 4.3). Four virtual markers were created to define the bat face, based on the existing bat markers plus the measured depth of the bat in the anterior-posterior axis of the bat's local coordinate system. Any curvature or bowing of the bat face was neglected due to their minimal magnitude, and the bat face was represented by a flat rectangular plane.

Curves were fitted to the post-impact phase of the raw unfiltered ball centre coordinate data separately against time in the vertical, anterior-posterior, and medio-lateral planes according to Eq. (1). The post-impact phase was defined as data between impact (identified from a change in the anterior-posterior and medio-lateral position of the ball for the forward drive and pull shots respectively) and any post-impact ball bounce (identified from a change in vertical direction of the ball). Separate Fourier series models were similarly fitted to the four corners of the bat face against time in the medio-lateral, anterior-posterior, and vertical planes, during the downswing. Time of impact was defined as the time at which the post-impact ball curves, plotted against time, passed through the mean position of the ball centre during the static pre-impact phase in its primary plane of motion (anterior-posterior for the forward drive, medio-lateral for the pull shot). Impact location was then calculated from the ball centre and bat face marker positions at the estimated impact time (calculated from the curve equations) using global to local coordinate system rotation matrices, allowing the determination of the location of the ball centre relative to the local coordinate system of the bat.

The goodness of fit (R^2 and RMSE) of each curve to the raw bat and ball centre coordinate data, and the difference between the measured and calculated impact locations in each plane were assessed as measures of accuracy within the methodology. Finally, differentiation of the post-impact curve equations enabled the calculation of resultant instantaneous post-impact ball speed (Appendix 3). This was compared to post-impact ball speed calculated via differentiation of ball position over a 40 ms time interval, in order to assess similarity between the two velocities, and thus validate the speed derived from the curve fitting methodology.

6.3.4 Stage 4 – Impact Location Calculation: Dynamic ball

6.3.4.1 Data Collection

Markers were applied to the ball and bat as described previously in Stage 3. The same single subject performed six batting strokes (three forward drives, three pull shots) against a bowling machine (BOLA Professional) with inbound speed on the approach to impact, calculated using differentiated ball position data over a 40 ms interval, of 24.1 ± 0.7 ms^{-1}. Impact location in each case was again derived from the impression left in a fine powder coating on the bat face (Figure 6.3) and digitised using Image-Pro Analyser software (Media Cybernetics Inc., MD, USA).

6.3.4.2 Data Reduction

The ball and bat marker position data were manually labelled and processed, and ball centre position was calculated and interpolated as in Stage 3. Curves were fitted to the pre- and post-impact phases of the raw unfiltered ball centre coordinate data separately against time in the vertical, anterior-posterior, and medio-lateral planes according to Eq. (1). The pre-impact phase was defined as data between ball bounce and impact (identified from a change in the vertical and anterior-posterior directions of the ball respectively), while the post-impact phase occurred between impact and any post-impact ball bounce (identified from a change in vertical direction of the ball). Separate Fourier series models were fitted to the four corners of the bat face against time in the medio-lateral, anterior-posterior, and vertical planes during the downswing, and the bat face represented as a flat rectangular plane as in Stage 3. Time of impact was determined as the mean time at which the pre- and post-impact ball curves, plotted against time, intersected in the vertical and anterior-posterior planes (Figure 6.6). Data in the medio-lateral plane was not included in this section of the analysis due to the poor pre-impact R^2 fit values (mean 0.50 ± 0.49; see Stage 4 Results) found while curve fitting in this plane. Although fitting a curve to this data only produced a small RMSE (6.48 ± 2.4 mm), the poor fit values were attributed to the fact that the magnitude of the tracking errors was at times greater than actual ball displacement in this axis, as the ball was projected almost entirely anterio-posteriorly and vertically with minimal displacement in the medio-lateral axis. Impact location was then calculated from the ball centre and bat face marker positions at the estimated impact time (calculated from the curve equations) using global to local coordinate system rotation matrices, allowing the determination of the location of the ball centre relative to the local coordinate system of the bat.

The goodness of fit (R^2 and RMSE) of each curve to the raw bat and ball centre coordinate data, the difference in estimated impact time between curves in the vertical and anterior-posterior planes, and the difference between the measured and calculated impact locations in each plane were assessed as measures of accuracy within the methodology. As in Stage 3, a comparison between post-impact ball speed calculated via the curve fitting methodology and via differentiation over a 40 ms time interval was conducted to assess similarity between the two velocities, and thus validate the speed derived from the curve fitting methodology.

6.3.5 Stage 5 – The Effects of Impact Location on Shot Outcome

6.3.5.1 Data Collection

Twenty experienced male cricketers (22.5 ± 3.1 years, 1.82 ± 0.04 m, 80.0 ± 7.8 kg) participated in this investigation. Subjects ranged from premier league club batsmen to international standard players, thus a range of impact locations and ball velocities were generated. Markers were applied to the ball and each subject's own bat as described previously. Subjects performed a series (mean 14 ± 4) of range hitting trials against the same bowling machine as used in Stage 4 (inbound speed on the approach to impact of 25.0 ± 1.3 ms^{-1}), each time attempting to hit a forward drive for six straight down the ground. Only trials where the ball was successfully impacted in a forward direction were selected for analysis, leaving a total of 239 trials.

6.3.5.2 Data Reduction

Marker data was processed as before, and curves fit to the pre- and post-impact phases (identified from the change in vertical anterior-posterior direction of ball trajectory as in Stage 4) according to Eq. (1). Fourier series models were again fit to the bat face marker positions, and the impact location calculated from the curve equations using the position of the bat face and ball centre markers at the mean time of intersection between the pre- and post-impact curves in the vertical and anterior-posterior planes as in Stage 4.

6.3.5.3 Data Analysis

Initially the goodness of fit (R^2 and RMSE) of each curve, and the difference in estimated impact time between curves in the vertical and anterior-posterior plane were established. The resultant instantaneous post-impact ball speed was also compared to ball speed calculated via differentiation of ball position over a 40 ms time interval as in Stages 3 and 4.

The calculated impact locations in the medio-lateral and vertical planes of the bat were then assessed against the resultant instantaneous post-impact ball speed from the curve equations; theoretically an impact further from the sweetspot should result in a slower post-impact ball speed. Firstly, the distances of impact from a virtual marker on the bottom corner of the bat face in the medio-lateral and vertical planes of the bat were plotted against resultant post-impact ball speed, and any trends investigated visually. A virtual sweetspot position was subsequently defined based on the work of Bower (2012), as being located on the midline of the bat in the medio-lateral plane, and 17.5 cm from the toe of the bat in the vertical plane. A Spearman's rank-order correlation coefficient ($\alpha = 0.05$) was then computed (due to non-normality in the impact location data) to assess the relationship between the absolute distance of impact from the sweetspot in both the medio-lateral and vertical planes, and the resultant post-impact ball speed derived from the curve equations. Finally, a total impact location score was calculated for each impact according to its location on the bat face in the medio-lateral and vertical planes combined, based on a method adapted from Bower (2012). Four rectangular sections were defined on the bat face (Figure 6.4) defining the proximity of the impact to the previously defined sweetspot. Each impact was then scored (from one to four) in terms of its location within the rectangular sections in the medio-lateral and vertical planes separately; the sum of these scores represented the total impact location score.

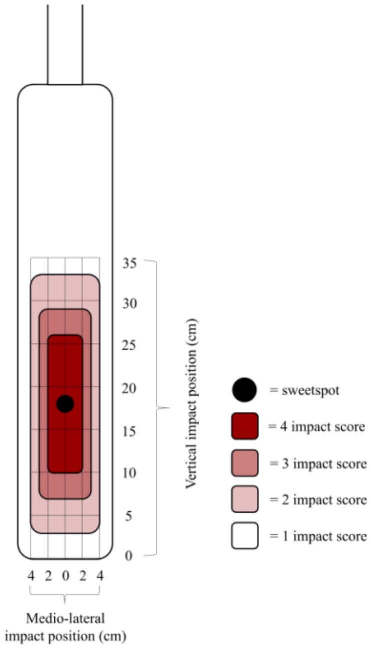


Figure 6.4: Sweetspot location and impact location scoring sections on the bat face.

Total impact location score for each stroke was then compared with the resultant post-impact ball speed derived from the curve equations, and again a Spearman's rank-order correlation coefficient ($\alpha = 0.05$) was computed to assess the relationship between the two variables. In order to check for any confounding variables that may coincidentally cause a measured increase in post-impact ball speed, pre-impact bat and ball speed were also assessed against the absolute distance of impact from the previously defined sweetspot via Spearman's rank-order correlation coefficients ($\alpha = 0.05$).

Next, post-impact bat twist about its longitudinal axis was assessed for each batting stroke, and compared to the calculated impact location in the medio-lateral plane from the curve fitting methodology. Initially the angular velocity of the bat about its longitudinal axis was calculated, and the absolute peak between impact and 0.02 s after impact was defined. A measure of post-impact bat twist was then determined as the difference between the peak measured bat twist angular velocity and the mean pre-impact bat twist angular velocity (averaged between 0.02 and 0.012 s before impact). It was hypothesised that impacts occurring across the majority of the bat face would display a linear fit, where impacts further from the midline generate larger measures of bat twist. However, it was also reasoned that impacts occurring on the edge of the bat would generate less twist because the ball is likely to experience more of an oblique or glancing impact; this would make the overall fit to the data cubic. Again the goodness of fit (R^2 and RMSE) of the curve to the measured data was assessed in order to validate this hypothesis.

Finally, the post-impact ball direction relative to a line perpendicular to the bat face at the time of impact was calculated for each trial, and compared to the impact location in the medio-lateral plane of the bat. Both the angle of the bat face and post-impact ball direction were calculated relative to the global coordinate system, from the existing local bat coordinate system at the time of impact, and from the post-impact ball curves respectively. It was hypothesised that impacts occurring further from the midline of the bat would create a larger offset between the angle of the bat face and the post-impact direction of the ball due to increased bat twist at the time of impact, whereas impacts occurring near the midline would propel the ball approximately perpendicular to the bat face after impact. However, impacts occurring near the edge of the bat, thus experiencing a more oblique impact and less bat twist, were expected to generate additional deviation from the target compared to those slightly nearer the midline. The oblique nature of the impact is thought to cause the ball to slide off the face and edge of the bat, generating lower bat twist, but departing at an angle further from the intended target line. This was therefore again expected to conform to a cubic fit, which was assessed using R^2 and RMSE measures for the goodness of fit.

6.4 Results

6.4.1 Stage 1 – Spatial Reconstruction Accuracy

RMSE values from the mean separation between the three marker pairs on the calibration wand averaged 0.3 ± 0.0 mm.

6.4.2 Stage 2 – Ball Flight Tracking

R^2 and RMSE values for the goodness of fit of the pre-impact ball curves averaged 0.97 ± 0.05 and 8.3 ± 1.2 mm respectively (Table 6.1). Comparison of the calculated and measured ball impact locations on the mat resulted in mean absolute differences of 8.4 ± 3.0 and 6.6 ± 3.6 mm in the medio-lateral and vertical planes respectively.

Table 6.1: Goodness of fit statistics for pre-impact ball curves in ball tracking trials (mean ± SD).

	R^2	RMSE (mm)
Medio-lateral	0.91 ± 0.06	7.6 ± 2.5
Anterior-posterior	1.00 ± 0.00	9.6 ± 3.4
Vertical	1.00 ± 0.00	7.6 ± 2.1

6.4.3 Stage 3 – Impact Location Calculation: Static Ball

R^2 and RMSE values for the goodness of fit of the post-impact ball curves averaged 0.94 ± 0.14 and 5.1 ± 2.8 mm, while those for the bat curves averaged 0.99 ± 0.04 and 0.6 ± 0.3 mm respectively (Table 6.3).

Table 6.2: Goodness of fit statistics for ball and bat curves in static ball impact location trials (mean ± SD).

	R^2	RMSE (mm)
Ball medio-lateral post	0.99 ± 0.03	5.3 ± 2.4
Ball anterior-posterior post	1.00 ± 0.01	4.4 ± 1.7
Ball vertical post	0.84 ± 0.21	5.6 ± 3.9
Bat medio-lateral pre	0.98 ± 0.08	0.5 ± 0.2
Bat anterior-posterior pre	1.00 ± 0.00	0.7 ± 0.4
Bat vertical pre	1.00 ± 0.00	0.4 ± 0.2

Note: pre/post relates to pre-/post-impact phase curves.

Comparison of the calculated and measured ball impact locations on the bat face resulted in mean absolute differences of 4.8 ± 2.3 and 4.5 ± 3.2 mm in the medio-lateral and vertical planes of the bat respectively (Figure 6.5). The calculated perpendicular distance from the bat face to the ball centre at the moment of impact was also evaluated and compared with the ball radius (35 mm), finding a mean absolute difference of 10.7 ± 7.7 mm. Instantaneous post-impact ball speed derived from the curve equations for the six impact location trials was 27.6 ± 2.2 ms^{-1}. Comparison with ball speed calculated via differentiation of post-impact ball position data over a 40 ms time interval revealed an absolute difference of 0.3 ± 0.2 ms^{-1}.

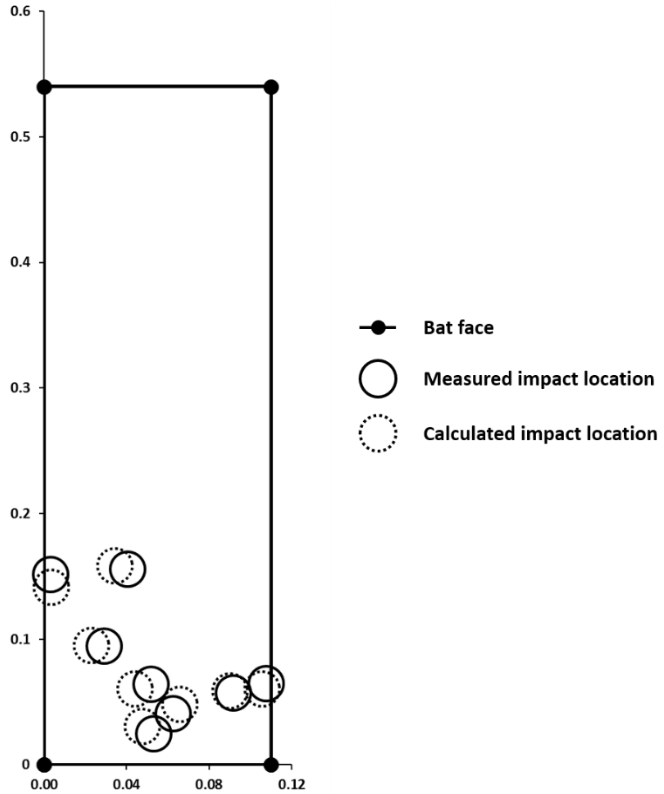


Figure 6.5: Measured and calculated impact locations in the static ball trials.

6.4.4 Stage 4 – Impact Location Calculation: Dynamic ball

R^2 and RMSE values for the goodness of fit of the pre- and post-impact ball curves averaged 0.91 ± 0.20 and 7.7 ± 1.4 mm, while those for the bat curves averaged 1.00 ± 0.00 and 0.8 ± 0.2 mm respectively (Table 6.3). Removal of the pre-impact medio-lateral ball curve fitting data, which was not used throughout the analysis, alters the mean R^2 and RMSE values to 0.99 ± 0.04 and 7.9 ± 2.3 mm respectively.

Table 6.3: Goodness of fit statistics for ball and bat curves in dynamic ball impact location trials (mean ± SD).

	R^2	RMSE (mm)
Ball medio-lateral pre	0.50 ± 0.49	6.5 ± 2.4
Ball medio-lateral post	0.97 ± 0.08	8.1 ± 2.9
Ball anterior-posterior pre	1.00 ± 0.00	8.7 ± 1.8
Ball anterior-posterior post	1.00 ± 0.00	9.6 ± 1.6
Ball vertical pre	0.99 ± 0.01	6.2 ± 1.7
Ball vertical post	0.97 ± 0.05	6.9 ± 2.1
Bat medio-lateral pre	1.00 ± 0.01	1.0 ± 0.5
Bat anterior-posterior pre	1.00 ± 0.00	0.8 ± 0.5
Bat vertical pre	1.00 ± 0.00	0.5 ± 0.3

Note: pre/post relates to pre-/post-impact phase curves

Assessment of the estimated impact time between curves (Figure 6.6) in the vertical and anterior-posterior planes showed a mean difference of 2.0 ± 2.3 ms. Comparison of the calculated and measured ball impact locations on the bat face resulted in mean absolute differences of 7.4 ± 4.7 and 9.2 ± 4.3 mm in the medio-lateral and vertical planes of the bat respectively (Figure 6.7). The calculated perpendicular distance from the bat face to the ball centre at the moment of impact was also evaluated and compared with the ball radius (35 mm), finding a mean absolute difference of 10.1 ± 12.6 mm. More detailed examination of the individual trials showed that one trial, with a calculated impact location 44 mm from the midline, thus on the edge of the bat and with the ball centre close to being in line with the plane of the bat face at the time of impact, substantially affected the calculated ball radius measurement. Removal of this trial reduced the absolute difference between the perpendicular distance from the bat face to the ball centre at the moment of impact and the ball radius (5.2 ± 4.1 mm). Instantaneous post-impact ball speed derived from the curve equations for the six impact location trials was 21.9 ± 4.7 ms^{-1}. Comparison with ball speed calculated via differentiation of post-impact ball position data over a 40 ms time interval revealed an absolute difference of 0.4 ± 0.6 ms^{-1}.

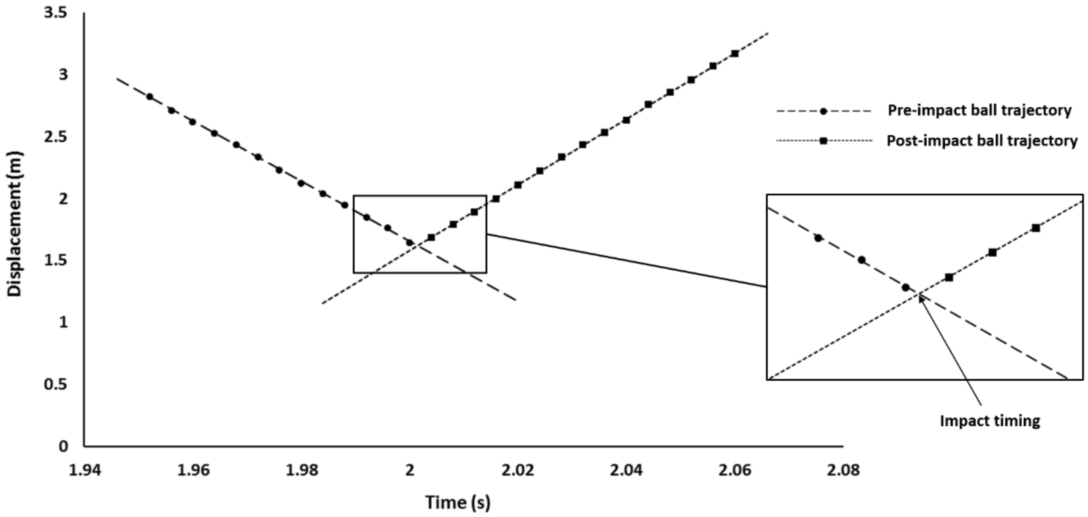


Figure 6.6: Pre- and post-impact ball curve fitting, and impact timing calculation.

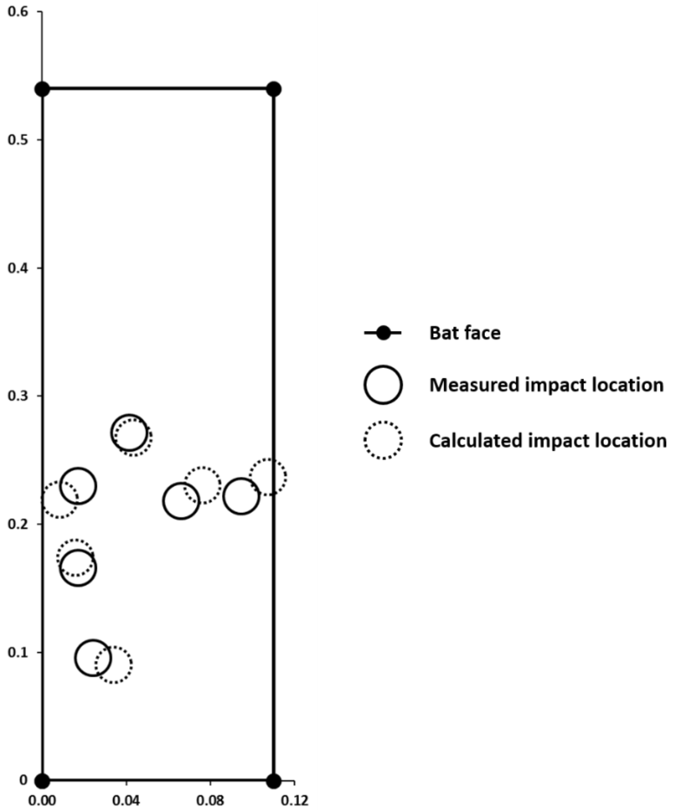


Figure 6.7: Measured and calculated impact locations in the dynamic ball trials.

6.4.5 Stage 5 – The Effects of Impact Location on Shot Outcome

R^2 and RMSE values for the goodness of fit of the pre- and post-impact ball curves averaged 0.99 ± 0.04 and 9.8 ± 4.3 mm, while the R^2 and RMSE values for the bat curves averaged 0.99 ± 0.03 and 1.0 ± 0.9 mm respectively (Table 6.4).

Table 6.4: Goodness of fit statistics for ball and bat curves in range hitting trials (mean ± SD).

	R^2	RMSE (mm)
Ball medio-lateral post	0.97 ± 0.07	10.3 ± 4.6
Ball anterior-posterior pre	1.00 ± 0.00	10.6 ± 4.2
Ball anterior-posterior post	0.99 ± 0.03	11.4 ± 5.0
Ball vertical pre	0.99 ± 0.03	8.4 ± 2.8
Ball vertical post	1.00 ± 0.02	8.2 ± 3.2
Bat medio-lateral pre	0.98 ± 0.06	1.0 ± 0.9
Bat anterior-posterior pre	1.00 ± 0.00	1.1 ± 1.1
Bat vertical pre	1.00 ± 0.01	0.8 ± 0.8

Note: pre/post relates to pre-/post-impact phase curves.

Assessment of the estimated impact time between curves in the vertical and anterior-posterior planes showed a mean difference of 1.3 ± 1.0 ms. Instantaneous post-impact ball speed derived from the curve equations for the 239 range hitting trials was 28.1 ± 4.2 ms^{-1} (range

17.8 – 39.5 ms^{-1}). Comparison with ball speed calculated via differentiation of ball position data, again over a 40 ms interval, displayed an absolute difference of 0.6 ± 0.6 ms^{-1}.

Visual inspection of the plots showing the distance of impact in the medio-lateral and vertical planes from a virtual marker on the bottom corner of the bat face against post-impact ball speed (Figure 6.8) indicated that both sets of data followed an approximate 'inverted U-shape' trend, suggesting the presence of an optimal impact location in both planes for generating high post-impact ball speed. A Spearman's rank-order correlation revealed significant moderate to strong negative relationships between the absolute distance of impact from the midline (r_s = -0.52, p < 0.01) in the medio-lateral plane and sweetspot (r_s = -0.45, p < 0.01) in the vertical plane, and post-impact ball speed. Plots displaying these relationships are shown in Figure 6.9. Analysis of these linear relationships also allows predictive equations for post-impact ball speed to be formed in the medio-lateral (Eq. 2) and vertical (Eq. 3) planes of the bat to be derived.

$$v = -112.41x + 32.06 \qquad (2)$$

$$v = -45.79y + 31.18 \qquad (3)$$

where v = post-impact ball speed; x = absolute distance of impact from the sweetspot in the medio-lateral plane; and y = absolute distance of impact from the sweetspot in the vertical plane.

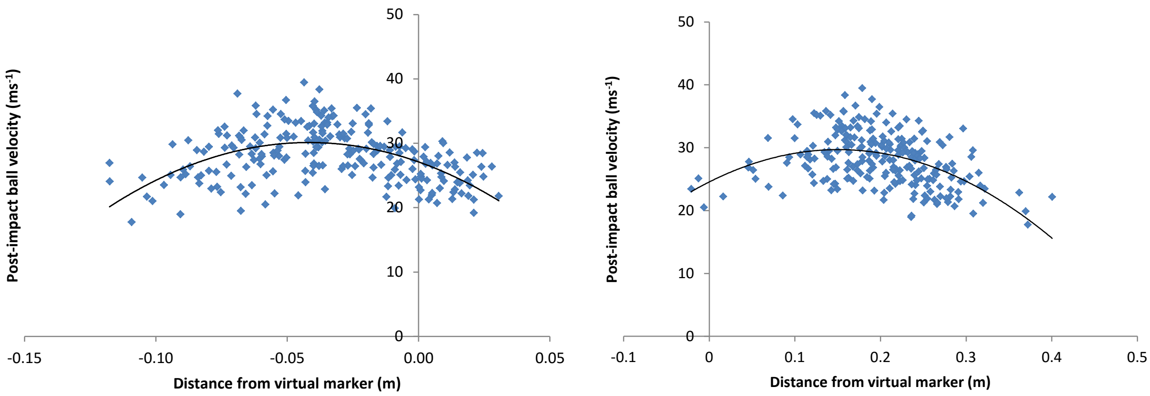


Figure 6.8: The distance of impact in the medio-lateral (left) and vertical (right) planes of the bat from a virtual marker on the bottom corner of the bat face against resultant post-impact ball speed.

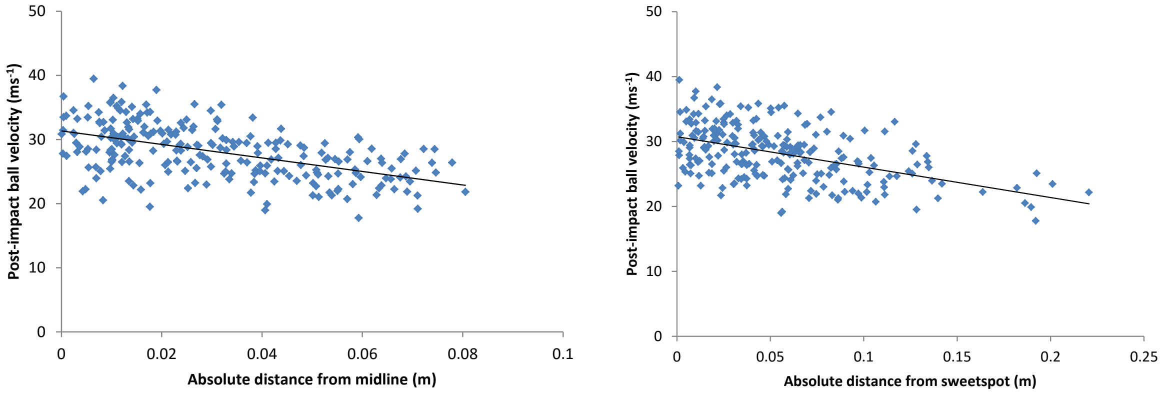


Figure 6.9: The absolute distance of impact from the midline (medio-lateral plane; left) and sweetspot (vertical plane; right) of the bat face against resultant post-impact ball speed.

Comparison of total impact location score with post-impact ball speed using a Spearman's rank-order correlation found a significant strong positive relationship (r_s = 0.67, p < 0.01) between the variables (Figure 6.10). Spearman's rank-order correlations between pre-impact bat and ball speed and absolute distance of impact from the midline (medio-lateral plane) and sweetspot (vertical plane) showed no relationships (-0.13 < r_s < 0.07, 0.66 < p < 0.92).

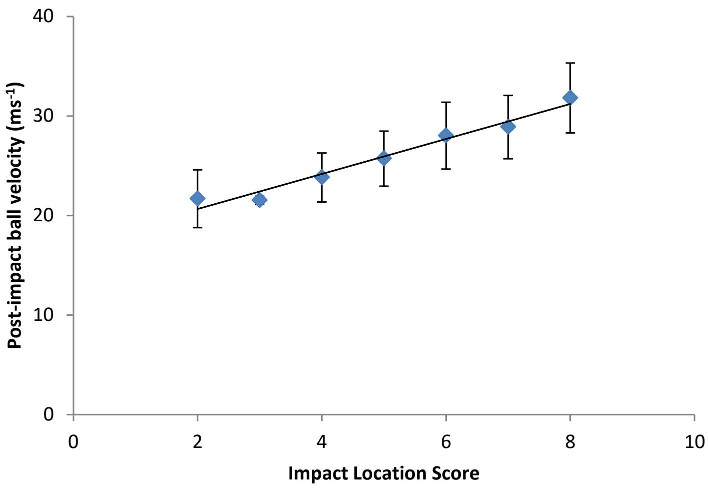


Figure 6.10: Total impact location score against resultant post-impact ball speed (mean ± SD).

Figure 6.11 shows a comparison of the distance of impact from the midline of the bat in the medio-lateral plane and the previously defined measure of post-impact change in the rate of bat polar rotation (twist). This displays a strong cubic fit, with an R^2 value for the goodness of fit of 0.89. Analysis of this cubic relationship also allows a predictive equation to be formed for the peak change in the rate of bat polar rotation according to the distance of impact from the midline of the bat (Eq. 4).

$$t = -3E + 07x^3 + 713182x^2 + 265293x - 1585.1 \quad (4)$$

where t = change in the rate of bat polar rotation; and x = absolute distance of impact from the midline in the medio-lateral plane.

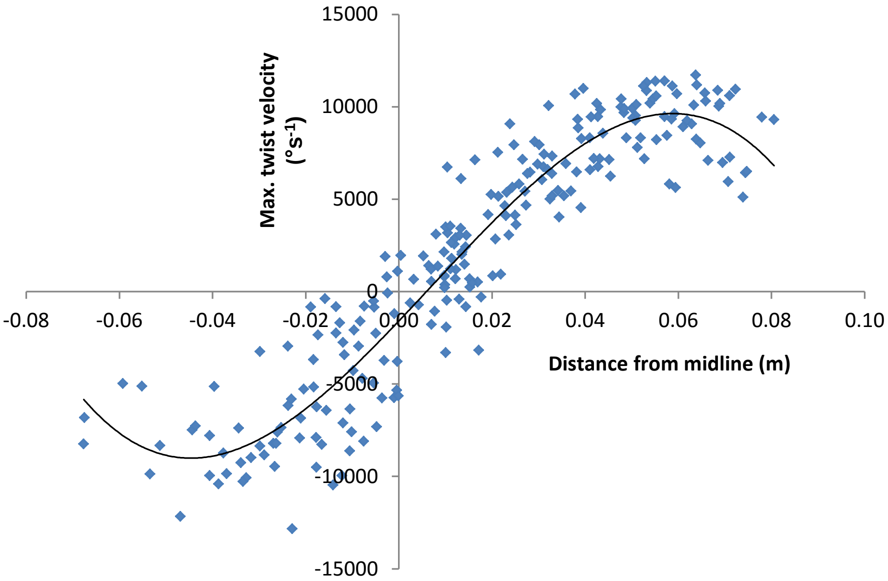


Figure 6.11: The distance of impact from the midline of the bat (medio-lateral plane) against the peak change in angular velocity of the bat about its longitudinal axis as a result of impact.

Finally, comparison of the difference between the post-impact ball direction and the angle of the bat face immediately prior to impact with the impact location in the medio-lateral plane of the bat revealed a strong cubic relationship (R^2 = 0.70; Figure 6.12). Analysis of this cubic relationship also allows a predictive equation to be formed for the deviation of the ball trajectory from a line perpendicular to the bat face at the time of impact according to the distance of impact from the midline of the bat (Eq. 5).

$$d = 61555x^3 - 682x^2 + 489.1x + 1.1 \quad (5)$$

where d = deviation of ball trajectory from a line perpendicular to the bat face at the time of impact; and x = absolute distance of impact from the midline in the medio-lateral plane.

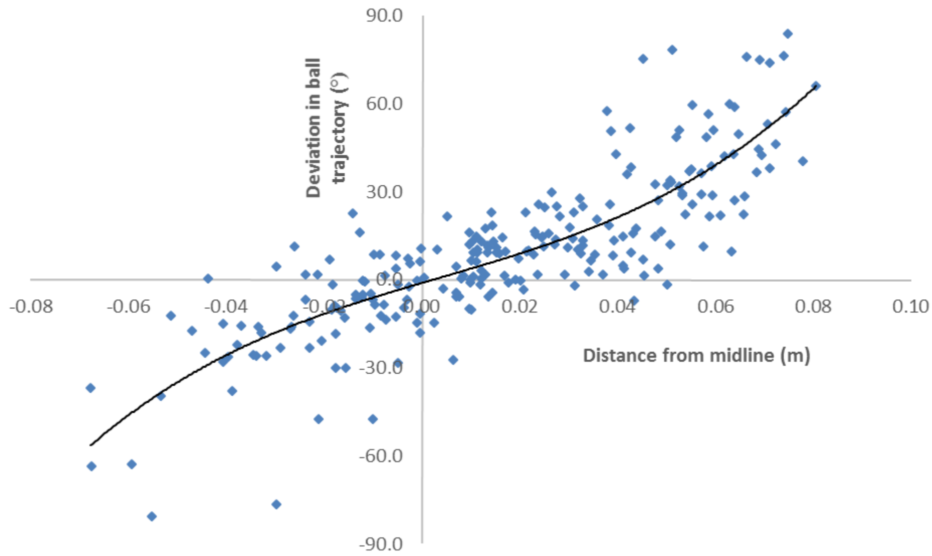


Figure 6.12: The difference in angle between the bat face immediately prior to impact and the post-impact ball direction against the distance of impact from the midline of the bat (medio-lateral plane).

6.5 Discussion and Conclusions

A curve fitting methodology for the determination of the impact location of a cricket ball on a bat face, as well as the identification of bat-ball contact timing and post-impact instantaneous ball speed, has been presented, and accuracy checks carried out for various steps of the process. Initial checks of the spatial reconstruction accuracy of the motion capture setup in Stage 1 revealed very small errors in marker separation, with a mean RMSE of 0.3 ± 0.0 mm. This indicates that any larger errors found in later stages of the checking procedures are unlikely to be as a result of the reconstruction accuracy of the motion capture system, and are therefore likely to be a function of the methodology itself.

The high mean R^2 and low mean RMSE values for all pre- and post-impact ball curves in Stages 2-5 justify the use of the logarithmic equation (Eq. 1), and demonstrate that such an equation is appropriate for modelling cricket ball trajectories shortly before and after impact. Any small errors in curve fitting, evidenced by non-perfect R^2 values, are most likely a result of errors in marker tracking of ball centre calculation. The lowest R^2 values were consistently found in the medio-lateral plane of ball motion, with the mean pre-impact medio-lateral R^2 value for the six dynamic ball impact location trials in Stage 4 falling as low as 0.50, thus justifying the removal of this data from the calculation of impact timing. This same curve however, had an RMSE of 6.5 mm, which was similar to the mean values across both the anterior-posterior and vertical planes. This highlights that the lower and more variable R^2 values, found particularly in the pre-impact medio-lateral ball curves, were simply due to the small displacements in this plane. Ball displacements were much greater in the anterior-posterior and vertical planes for the majority of trials, and so the same absolute error (reflected by similar RMSE) resulted in lower R^2 values for the medio-lateral curves. The same justification can be given to the slightly lower R^2 values found in the post-impact vertical ball curves in Stage 3, caused by small displacement of the ball centre in this plane in certain trials. Although assessment of the goodness of fit of the ball and bat curves during the range hitting trials (Stage 5) found similar R^2 fits to those in Stages 2-4, a slightly increased RMSE is evident across both ball and bat curves. This is most likely due to the higher ball (25.0 compared to 23.4 ms^{-1}) and bat distal endpoint speeds (25.7 compared to 20.7 ms^{-1}) seen in Stage 4, further increasing the difficulty in accurately tracking both ball and bat markers.

All mean RMSE values for pre- and post-impact ball curves in Stages 2-5 were less than 12 mm, indicating a high level of accuracy within the curve fitting procedure. The increased error magnitudes in comparison to measurements in Stage 1 involving the calibration wand are likely due to the added difficulty in accurately tracking the squares of tape positioned on a fast-moving spinning ball, and errors created by the ball centre calculation method used. This is exemplified by the higher R^2 and lower RMSE values found while fitting curves to the bat marker data, highlighting the relative simplicity in accurately tracking the position of markers travelling along a consistent trajectory in comparison to tape spinning around the circumference of a fast moving ball.

Measured errors in calculated impact location on the mat in Stage 2, and on the bat in Stages 3 and 4, were found to be similar in magnitude to the RMSE values found in the pre- and post-impact ball curve fitting stages of the methodology. This indicates that no additional major errors were generated through the calculation of the timing of curve intersection with a plane or another curve, the inclusion of the bat face marker locations, or the transformation of position data from a global to local coordinate system, therefore suggesting that the largest absolute errors are found in ball tracking and ball centre calculation. Small errors in Stages 3 and 4 could also be attributed to the assumption that the bat represents a flat plane, when in actual fact the majority of bats exhibit some 'bowing' or curvature across their face. This could slightly affect the accuracy of exact impact timing, and thus the impact location on the bat face.

The differences in estimated impact timing between the anterior-posterior and vertical planes were 2.0 ± 2.3 and 1.3 ± 1.0 s in Stages 4 and 5 respectively. The larger errors found in Stage 4 can be explained by the presence of a single trial, in which the pre- and post-impact change in vertical ball displacement is markedly smaller than in the remainder of the trials. As a result of this small change in displacement, any tracking errors present in the ball trajectory have a relatively large effect on the quality of curve fitting, as shown by the lower R^2 fit value in the vertical plane for this trial (0.92 ± 0.08) when compared to the remaining five trials (1.00 ± 0.00). Removal of this trial reduces the differences in estimated impact timing between the anterior-posterior and vertical planes in Stage 4 to 1.1 ± 0.8 ms. When considering the time between frames in this study (4 ms), and the 1.0 – 1.5 ms impact duration between bat and ball in cricket (Symes, 2006), the magnitude of these differences in estimated impact timing indicate that the curve fitting methodology produces a more accurate estimation of the timing of impact, and thus the impact location, than simply selecting the frame at which the ball centre is closest to the plane of the bat face. The proximity of the perpendicular distance from bat face to ball centre at the time of impact and the measured radius of a cricket ball in Stages 3 and 4 further enhances the credibility of the timing of impact calculations and calculated bat and ball position at this time.

When compared to differentiation over a 10 frame time interval (40 ms), the resultant speeds obtained via curve fitting in the Stages 3 and 4 impact location trials, and Stage 5 range hitting trials, revealed absolute differences of 0.3 ms^{-1}, 0.4 ms^{-1}, and 0.6 ms^{-1} respectively. While these differences do not indicate an error in either speed measure, as there are inherent differences between the calculated average and instantaneous speeds, their similarity indicates a high level of accuracy in determining post-impact ball speed from the curve fitting methodology.

The 'inverted U-shape' trend found in Figure 6.8 indicates the presence of an optimal impact location, or sweetspot in both the medio-lateral and vertical planes, where impact either side of that point generates a lower resultant ball speed. This is confirmed by the moderate to strong linear correlations found between the absolute distances of impact from the previously defined sweetspot in both the medio-lateral and vertical planes of the bat against resultant post-impact ball speed (Figure 6.9). This finding agrees with the work of Symes (2006), who found a linear decrease in coefficient of restitution (COR) with impacts further from the sweetspot in the vertical plane. The fact that the peak measured post-impact ball speed occurred at the virtual sweetspot in the vertical plane, supports the work of Bower (2012) and

Symes (2006), in finding the highest rebound speeds to occur during impacts approximately 17.5 cm from the toe of the bat. Investigation of the predictive equations for these relationships revealed that impacts occurring as little as 2 cm from the midline of the bat in its medio-lateral axis, or 5 cm from the sweetspot in the vertical plane, cause a reduction in post-impact ball speed of around 8% in comparison to an impact directly on the sweetspot.

The total impact score measure provided a stronger correlation with resultant post-impact ball speed ($r_s = 0.67$) than either of the planar measures alone ($r_s = -0.52, -0.45$), highlighting that it is a combination of the distance of impact from the sweetspot in both planes that truly affects the post-impact ball speed. Although these two variables have been shown to be strongly correlated, many other factors such as pre-impact bat and ball speed are also likely to have an effect on resultant post-impact ball speed; this can be seen as accounting for the imperfect relationships displayed here. Further correlations between pre-impact bat and ball speed and absolute distance of impact from the sweetspot showed either very weak or no relationships, suggesting a causal relationship between impact location and post-impact ball speed that isn't coincidentally caused by an increase in pre-impact bat or ball speed.

Comparison of the distance of impact from the midline of the bat in the medio-lateral plane with the peak change in the rate of bat polar rotation (twist) of the bat showed a strong cubic relationship ($R^2 = 0.89$) in line with the hypothesis. This indicates that for impacts occurring across the majority of the bat face, an increased distance of impact from the midline of the bat generates a greater peak change in the rate of bat polar rotation (as in the study by Symes; 2006), while impacts occurring near the edge of the bat generate less twist due to more of an oblique impact. Although the study performed by Symes (2006) states a predominantly linear relationship between impact location and the rate of bat polar rotation, there is some evidence of a reduction in bat twist with impacts towards the edge of the bat. It is also possible that the non-normal nature of impacts in this study, and the increased momentum created during impact by the fast-moving bat, are the cause of the comparatively marked decrease in bat twist during impacts towards the edge of the bat face. This suggests that, while future studies may be able to assess post-impact bat twist as a measure of success in cricket batting, researchers should take care when interpreting impacts occurring near the edge of the bat, as the twist magnitude alone is likely to be misleading.

Finally, the cubic relationship ($R^2 = 0.68$) found when comparing the post-impact ball direction relative to the angle of the bat face immediately prior to impact with the impact location in the medio-lateral plane of the bat, indicates a similar trend for impacts across the majority of the bat face as the relationship between impact location and bat twist. Impacts occurring further from the midline of the bat in the medio-lateral plane caused the ball to depart on an unwanted trajectory away from a line perpendicular to the bat face, most likely due to increased bat twist. However, impacts occurring towards the edge of the bat displayed a marked increase in deviation in ball trajectory from the intended target line. As suggested in the hypothesis, this is most likely due to the oblique nature of the impact causing the ball to slide off the face and edge of the bat, generating less bat twist, but causing an increased deviation of the ball trajectory from a line perpendicular to the bat face at impact. Investigation of the predictive equations for bat twist and post-impact ball direction revealed that impacts as little as 2 cm away from the midline of the bat in its medio-lateral plane generated a peak change in the rate of bat polar rotation of around 4000°s^{-1}, causing the ball to depart approximately 11° away from the intended trajectory according to the angle of the bat face immediately prior to impact.

In conclusion, the curve fitting methodology has been shown to possess sufficient accuracy in order to suitably calculate the impact location of a cricket ball on a bat face from three-dimensional motion capture data. This methodology can therefore be used with confidence to assess individual shot outcome in later studies. Further investigation of the effects of impact location on resulting post-impact bat and ball motion has shown batsmen to possess a very small margin for error in terms of impact location in order to generate their intended shot outcome. Impacts occurring as little as 2 cm from the midline of the bat in its medio-lateral axis, or 5 cm from the sweetspot in the vertical plane, have been found to cause a reduction in post-impact ball speed of around 8% in comparison to an impact directly on the sweetspot. Impacts away from the midline of the bat in its medio-lateral plane have also been found to cause the bat to twist, and the ball to depart on an unintended trajectory, with an impact 2 cm from the midline being found to generate a peak angular velocity of the bat about its longitudinal axis of around 4000°s^{-1} causing the ball to depart approximately 13° away from the intended trajectory according to the angle of the bat face immediately prior to impact. This study therefore not only provides researchers with a methodology to calculate the impact location of a cricket ball on a bat, but also helps gain an understanding of the accuracy required in a batting shot in order to gain a successful impact.

6.6 Chapter Summary

This chapter has effectively devised and validated a methodology for the accurate determination of the impact location of a cricket ball on the bat face, as well as the identification of bat-ball contact timing and post-impact instantaneous ball speed using three-dimensional motion capture data. It has also investigated the effects of a varying impact location on resulting shot outcome in terms of resulting post-impact bat twist, ball speed, and ball direction, in order to understand the accuracy required in a batting shot to gain a successful outcome. This methodology and understanding can now be taken forward into future studies assessing the kinematic features of play related to success in cricket batting.

CHAPTER 7

ASSESSING MOVEMENT VARIABILITY IN CRICKET BATTING

7.1 Introduction

Although the concept of movement variability in sporting actions has been investigated by a number of researchers across a range of different sports, as discussed in section 2.7, there continues to be conflicting evidence as to whether expert performers exhibit lower or higher movement variability. While conventional control theory suggests that variability in movement patterns is unwanted noise caused by redundancy in the sensorimotor system (Newell & Corcos, 1993), ecological approaches to motor control propose that the presence of some variability in movement could be functional, helping athletes to create flexible movement patterns and adapt to perturbations throughout their action (Hamill et al., 1999; Bartlett et al., 2007; Wilson et al., 2008). Hiley et al. (2013) found expert high bar gymnasts to possess lower variability in the mechanically important aspects of technique than lesser skilled gymnasts, while demonstrating more variability in some of the less important aspects. The authors suggested this allowed the expert athletes to cope with perturbations in their swing through feedback control, and to maintain the precise timing and coordination of swings required for high performance.

In the only study on cricket batting considering aspects of movement variability, Weissensteiner et al. (2011) found highly skilled batsmen to maintain higher performance outcomes and temporal consistency in the downswing phase of their bat swing, while exhibiting increased temporal variability during the backswing. The authors found this pattern to be reversed for the lesser skilled batsmen who showed greater variability during the downswing phase than the backswing, suggesting experts strive to maintain a consistent downswing above all else due to its importance to overall shot success.

Whilst there is clearly contradiction between the two major theories of movement variability, both agree that expertise is associated with a reduction in outcome variability, and that measured movement variability decreases during the early stages of learning a movement as the athlete begins to adopt a movement strategy. Whether this decrease in variability continues towards expertise, or increases again to form the 'U' shape relationship found by Wilson et al. (2008), perhaps depends on the complexity and the need for adaptability during the task being investigated (Hiley et al., 2013).

As such, the aim of this study was to begin to quantify the measured variability of elite and amateur cricket batsmen hitting both forward drive and pull shots in two different situations; against a bowling machine and hitting a static ball off a batting tee. The variability in delivery characteristics and shot outcome would be quantified and assessed, along with the variability in timing of some critical aspects of movement. This would allow initial investigation to occur into the variability present within kinematic variables throughout each batting shot. Particular consideration will be given to the presence of either increased or decreased variability within the hitting action for both expert and lesser skilled batsmen, and between the two delivery methods investigated. It was hoped this would begin to identify the key aspects of technique in each batting shot investigated, and highlight the areas in which elite batsmen gain a performance advantage over amateurs.

7.2 Methodology

7.2.1 Subjects

Seventeen cricket batsmen (mean ± SD: age = 22.1 ± 2.9 years; height = 1.82 ± 0.04 m; mass = 80.0 ± 8.3 kg) participated in this investigation. Subjects were split into two distinct groups according to their current playing level; elite and amateur. The elite group consisted of ten batsmen from the ECB elite and developmental playing squads, including one player from the current England Lions squad, three county players, and six that had represented England under 19's. The amateur group consisted of five premiership standard club batsmen and two lower league club batsmen. In this case an amateur group was included in an attempt to understand the differences between the two groups, and although against the initial aims of the research, may help extract the key common factors for success amongst the elite group.

7.2.2 Data Collection and Processing

Each batsman hit a series of forward drives ([BM] n = 12; [SB] n = 10) and pull shots ([BM] n = 12; [SB] n = 10) in two different situations; against a bowling machine (BM) and hitting a static ball off a batting tee (SB) as described in section 3.9.2. In each case the batting tee was positioned as desired by the batsman in terms of being suitable for the shot being performed, and the bowling machine was set up to deliver balls in an appropriate area for consistent repetition of the shot in question. Batsmen were encouraged at each stage to perform their shots as they would in a match environment. Each batting shot was captured by an 18 camera Vicon motion analysis system and three high-speed video cameras, all operating at 250 Hz as outlined in section 3.7. Sixty-two retro reflective markers were positioned on the body, bat, ball, and stumps (section 3.6). Trials were then reconstructed, manually labelled and filtered (section 4.3), before a biomechanical model was applied (section 4.4) and a series of key events automatically identified for each shot type (section 4.5.2).

7.2.3 Data Reduction

Only trials with suitable data quality and where a successful impact between the bat and ball, according to the scale proposed by Weissensteiner et al. (2009), were selected for analysis ([BM] n = 9.2 ± 1.4 drives, 9.4 ± 1.5 pulls; [SB] n = 9.7 ± 0.7 drives, 9.2 ± 1.4 pulls). This reduction was performed such that simple comparison between similar SB and BM trials could be conducted, without consideration of the number of successful and unsuccessful trials in each group. A series of variables common to both the static ball and bowling machine trials were then extracted from the biomechanical model for each batting shot (a subset of those presented and defined in section 4.5.3). Variables were divided into four distinct sections; delivery characteristics, shot outcome, event timings, and kinematic variables. While delivery characteristics was included in the analysis, the only variable suitable for comparison between static ball and bowling machine trials was the ball's position at impact, due to the stationary nature of the ball in the static ball trials. This was therefore used as the sole variable in the delivery characteristics category. More complete variable sets were used in the shot outcome and movement timing categories, including measures of impact location, bat speed, ball speed and direction, as well as each common timing variable for comparison across each batting shot. Due to the potentially vast number of possible kinematic variables, and the desire for simplicity of analysis in this initial study, only four kinematic variables were assessed; the angle of the bat, the angle formed between the wrists and bat related to wrist cocking, and the angle of the front and back elbows. These were chosen as they were deemed important across both batting shots to the eventual outcome, with movement about the wrist and elbow joints creating the majority of bat movement during the swing. Having selected the variables to be assessed, each variable set was then taken forward for statistical analysis.

7.2.4 Statistical Analysis

Initially mean and standard deviation values were calculated for each variable and all batsmen across each of the trial types previously outlined. All further statistical analysis was performed within SPSS v.22 (SPSS Corporation, USA). The skill level of each batsman was coded as a nominal factor, i.e. elite group and amateur group. Repeated measures multivariate analyses of variance (MANOVA) were conducted in order to identify significant differences in terms of variability between the two skill level groups and delivery methods, with skill level assessed as a between groups factor and delivery method assessed as a within group factor. Separate MANOVA's were undertaken for each set of variables; delivery characteristics, shot outcome, and event timings. In each case the correlation between dependent variables was found to be reasonable, and displayed no multicollinearity. While each of the datasets displayed some minor violations in the non-normal distribution of two dependent variables when divided into shot type and skill group, further processing and correction of these variables was deemed unnecessary given the suitability of the majority of data for this analysis. Equally there was a minor violation in terms of between groups homogeneity of variance for two dependent variables throughout the analysis, however Welch's F adjustments showed that this had no effect on the observed outcome. These violations are most likely a result of the relatively small number of subjects in each group.

In the case of the kinematic variables, due to the larger number of dependent variables and time intervals included, a single repeated measures MANOVA analysis was not suitable. In fact, further analysis suggested a number of violations to the assumptions of MANOVA throughout the data, including the assumption of reasonable correlation between dependent variables ($-0.4 < r < 0.9$), normal distribution of dependent variable data, and between groups homogeneity of variance. This is likely a result of the relatively low number of subjects in each group of this study. As such, statistical analysis of kinematic data was not conducted, and a simple visual inspection carried out instead. While this clearly lacks the scientific rigour of a statistical test, it was thought to be suitable in this case given the more investigative and descriptive nature of this initial variability study.

7.3 Results

Results are presented for the forward drive and pull shots in four distinct categories; delivery characteristics, shot outcome, movement timings, and kinematics throughout each stage of the batting shot.

7.3.1 Forward Drives

7.3.1.1 Delivery Characteristics

Ball position at impact in the static ball trials was found to be very consistent for each subject, though more variable in the bowling machine trials (Table 7.1). Repeated measures multivariate analysis revealed a significant multivariate effect for delivery method ($V = 0.966$, $F(3, 13) = 124.71$, $p < 0.001$), but not for skill level group or the interaction of delivery method and group. Within group univariate analyses indicated that ball position at impact in the X ($F(1, 15) = 97.79$, $p < 0.001$), Y ($F(1, 15) = 151.29$, $p < 0.001$), and Z ($F(1, 15) = 312.31$, $p < 0.001$) directions was significantly more variable in the bowling machine trials than the static ball trials.

Table 7.1: Ball position at impact for the static ball (SB) and bowling machine (BM) forward drives (mean ± SD).

Group	Delivery Method	X (m)	Y (m)	Z (m)
Elite	SB	0.076 ± 0.027*	1.943 ± 0.048*	0.157 ± 0.007*
	BM	0.272 ± 0.138*	1.765 ± 0.151*	0.393 ± 0.096*
Amateur	SB	0.167 ± 0.030*	1.879 ± 0.053*	0.167 ± 0.004*
	BM	0.241 ± 0.130*	1.621 ± 0.149*	0.416 ± 0.111*

Note: * denotes a significant difference ($p < 0.05$) between delivery methods.

7.3.1.2 Shot Outcome

Repeated measures MANOVA revealed a significant multivariate effect for delivery method ($V = 0.955$, $F(5, 11) = 46.88$, $p < 0.001$) in terms of variability in shot outcome variables. No significant effects were found for skill level group or the interaction between delivery method and group. Within group univariate analyses showed that the impact location in the medio-lateral ($F(1, 15) = 20.28$, $p < 0.001$) and vertical ($F(1, 15) = 220.38$, $p < 0.001$) planes of the bat were less variable in the static ball trials than the bowling machine trials. Bat speed ($F(1, 15) = 25.40$, $p < 0.001$), resulting ball speed ($F(1, 15) = 86.50$, $p < 0.001$), and ball direction

(F(1, 15) = 35.54, $p < 0.001$), were also found to be significantly less variable in the static ball condition than when facing the bowling machine (Table 7.2).

Table 7.2: Shot outcome variables for the static ball (SB) and bowling machine (BM) forward drives (mean ± SD).

Group	Delivery Method	Impact loc. X (m)	Impact loc. Y (m)	Bat speed (ms^{-1})	Ball speed (ms^{-1})	Ball direction (°)
Elite	SB	0.017 ± 0.013*	0.119 ± 0.011*	22.23 ± 0.73*	23.24 ± 0.99*	-1 ± 4*
	BM	0.009 ± 0.023*	0.032 ± 0.063*	19.62 ± 1.21*	19.84 ± 2.83*	-20 ± 23*
Amateur	SB	0.017 ± 0.014*	0.097 ± 0.014*	21.73 ± 0.73*	19.09 ± 1.09*	-3 ± 6*
	BM	0.016 ± 0.020*	0.056 ± 0.073*	19.37 ± 1.53*	18.39 ± 3.17*	-23 ± 29*

Note: * denotes a significant difference ($p < 0.05$) between delivery methods.

Although no significant multivariate effects were found for skill level group in terms of shot outcome, further visual inspection of the data revealed some interesting trends. While the difference in variability in impact location between delivery methods is visually evident (Figure 7.1), there is also some evidence of the elite group displaying lower variability in impact location in the vertical plane, particularly when facing the bowling machine. A similar trend is found when examining post-impact ball speed and direction, with the elite group seeming to be less variable, although again this is non-significant.

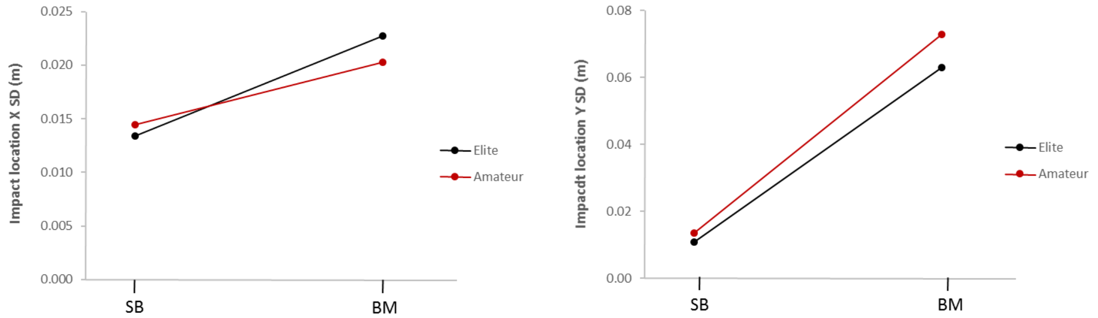


Figure 7.1: Variability (SD) in impact location in the medio-lateral (X) and vertical (Z) planes from the sweetspot for elite and amateur groups in the static ball (SB) and bowling machine (BM) forward drives.

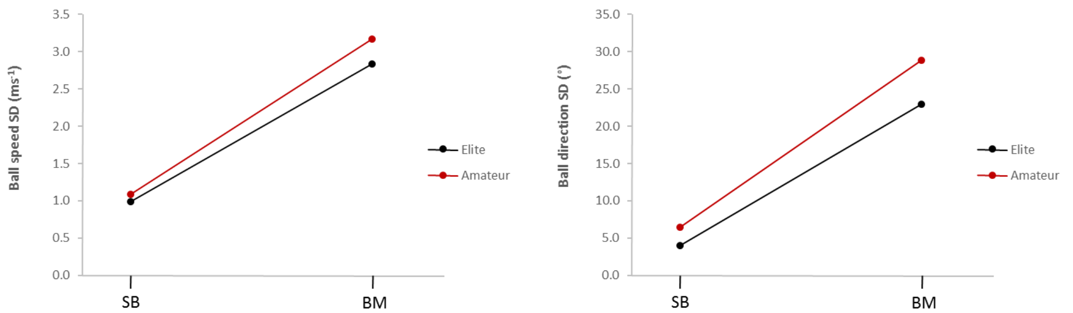


Figure 7.2: Variability (SD) in post-impact ball speed and direction for elite and amateur groups in the static ball (SB) and bowling machine (BM) forward drives.

7.3.1.3 Movement Timings

Repeated measures MANOVA revealed a significant multivariate effect for delivery method ($V = 0.745$, $F(4, 12) = 8.75$, $p < 0.01$) in terms of variability in movement timing variables. No significant effects were found for skill level group or the interaction between delivery method and group. Within group univariate analyses indicated that the timing of the commencement ($F(1, 15) = 16.78$, $p < 0.01$) and completion ($F(1, 15) = 37.60$, $p < 0.001$) of the forward stride were significantly less variable in the static ball trials than the bowling machine trials, however no significant differences in terms of variability between delivery methods were found for the timing of the bat swing (Table 7.3). Inspection of the data also reveals that the timing of the start of the downswing, in both static ball and bowling machine conditions, was the most consistent and therefore least variable event, displaying temporal variability of just 0.013 s and 0.016 s respectively.

Table 7.3: Movement timing variables for static ball (SB) and bowling machine (BM) forward drives (mean ± SD).

Group	Delivery Method	BS start (s)	Stride start (s)	DS start (s)	Stride end (s)
Elite	SB	0.574 ± 0.031	0.540 ± 0.018*	0.208 ± 0.012	0.086 ± 0.016*
	BM	0.440 ± 0.028	0.426 ± 0.024*	0.185 ± 0.017	0.049 ± 0.040*
Amateur	SB	0.645 ± 0.031	0.560 ± 0.017*	0.219 ± 0.016	0.082 ± 0.014*
	BM	0.425 ± 0.033	0.422 ± 0.026*	0.184 ± 0.016	0.057 ± 0.033*

Note: * denotes a significant difference ($p < 0.05$) between delivery methods.

7.3.1.4 Kinematics

Visual inspection of the variability data for bat angle (Figure 7.3) revealed several interesting trends. In comparing the two delivery methods assessed, it is evident that while bat angle variability decreased throughout the shot towards impact in the static ball trials, variability in the bowling machine trials was found to either decrease or stay relatively consistent up until the commencement of the downswing, then increase rapidly up to the point of impact.

Assessment of the difference between skill level groups suggests that while the amateur group displayed relatively high variability in bat angle in their stance and at the commencement of the backswing, the elite group were more consistent across both delivery methods. Both skill level groups also reached the same low level of variability in bat angle at the time of impact when hitting the static ball, with the amateur group showing a much sharper reduction in measured variability throughout the shot. Against the bowling machine however, while both groups again reached a similar level of variability in bat angle at the point of impact, at the commencement of the downswing the measured variability exhibited by the amateur group had reached its lowest point, while the variability in the elite group was found to be already increasing above that of the amateur group.

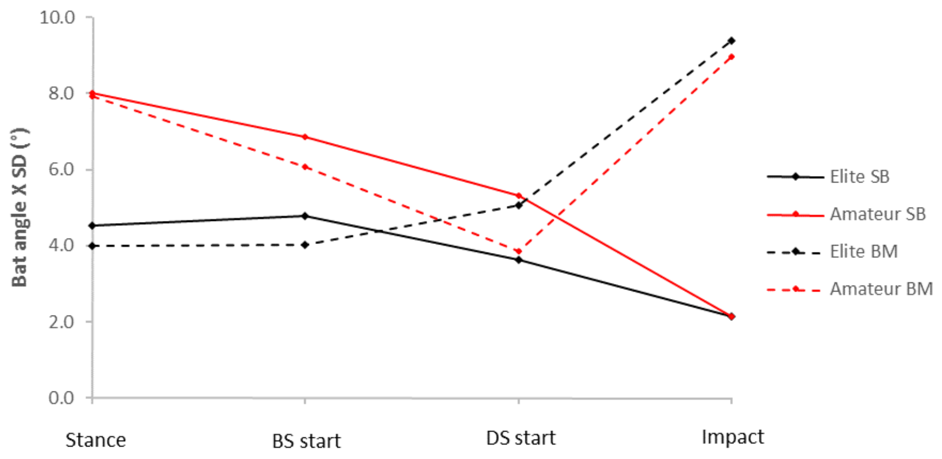


Figure 7.3: Variability (SD) in bat angle X at key time intervals throughout the static ball (SB) and bowling machine (BM) forward drives.

Examination of the variability data for wrist cocking angle, front elbow angle, and back elbow angle (Figure 7.4), reveals similar trends to the bat angle assessment. For both the wrist cocking angle and front elbow angle there is no real discernible difference between skill level groups in either the static ball or bowling machine trials. Measured variability in the static ball trials remained relatively consistent throughout the shot for both the wrist cocking angle and front elbow angle. In the bowling machine trials, the measured variability for all joint angles was again found to rapidly increase in the approach to impact, with the absolute variability exhibited in the front elbow angle reaching a higher peak than both the wrist cocking angle and the back elbow angle.

The patterns of variability in the back elbow angle (Figure 7.4) were very similar to those of the bat angle (Figure 7.3). While the elite group were relatively consistent in the angle of their back elbow during their stance and at the start of the backswing, the amateur group were more variable at this stage. Despite this, both groups were again found to display a similar level of variability at the commencement of the downswing and at the time of impact.

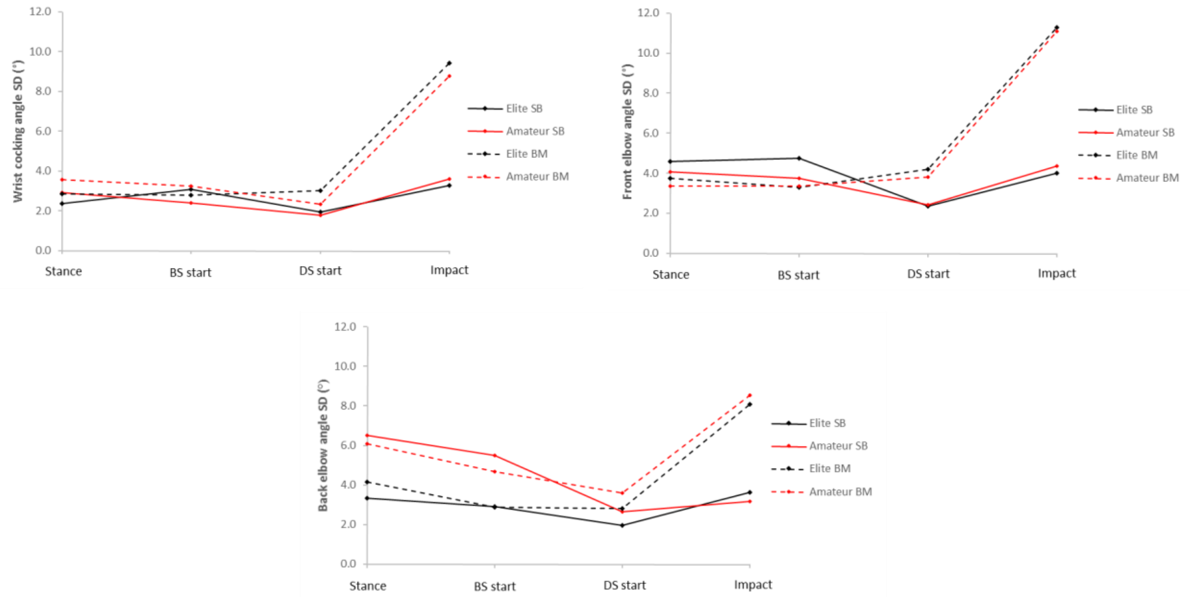


Figure 7.4: Variability (SD) in wrist cocking angle, front elbow angle X, and back elbow angle X at key time intervals throughout the static ball (SB) and bowling machine (BM) forward drives.

7.3.2 Pull Shots

7.3.2.1 Delivery Characteristics

As in the forward drives, ball position at impact in the pull shot trials was found to be very consistent in the static ball condition, though more variable in the bowling machine trials (Table 7.4). Repeated measures MANOVA revealed a significant multivariate effect for delivery method ($V = 0.983$, $F(3, 13) = 252.04$, $p < 0.001$), but not for skill level group of the interaction of group and delivery method. Within group univariate analyses indicated that ball position at impact in the X ($F(1, 15) = 134.47$, $p < 0.001$), Y ($F(1, 15) = 190.77$, $p < 0.001$), and Z ($F(1, 15) = 353.98$, $p < 0.001$) directions was significantly more variable in the bowling machine trials than the static ball trials.

Table 7.4: Ball position at impact for the static ball (SB) and bowling machine (BM) pull shots (mean ± SD).

Group	Delivery Method	X (m)	Y (m)	Z (m)
Elite	SB	0.023 ± 0.023*	2.036 ± 0.023*	1.189 ± 0.007*
	BM	0.385 ± 0.178*	1.804 ± 0.142*	1.448 ± 0.125*
Amateur	SB	0.023 ± 0.024*	1.792 ± 0.045*	1.199 ± 0.005*
	BM	0.274 ± 0.145*	1.570 ± 0.150*	1.190 ± 0.119*

Note: * denotes a significant difference ($p < 0.05$) between delivery methods.

7.3.2.2 Shot Outcome

Repeated measures MANOVA revealed a significant multivariate effect for delivery method ($V = 0.980$, $F(5, 11) = 105.40$, $p < 0.001$) in terms of variability in shot outcome variables. No significant effects were found for skill level group or the interaction between delivery method and group. Within group univariate analyses showed that the distance of ball impact from the sweetspot in the medio-lateral ($F(1, 15) = 5.87$, $p < 0.05$) and vertical ($F(1, 15) = 218.99$, $p < 0.001$) planes of the bat were less variable in the static ball trials than the bowling machine trials. Bat speed ($F(1, 15) = 41.13$, $p < 0.001$), resulting ball speed ($F(1, 15) = 64.76$, $p < 0.001$), and ball direction ($F(1, 15) = 205.20$, $p < 0.001$), were also found to be significantly less variable in the static ball condition than when facing the bowling machine (Table 7.2).

Table 7.5: Shot outcome variables for the static ball (SB) and bowling machine (BM) pull shots (mean ± SD).

Group	Delivery Method	Impact loc. X (m)	Impact loc. Y (m)	Bat speed (ms^{-1})	Ball speed (ms^{-1})	Ball direction (°)
Elite	SB	0.016 ± 0.018*	0.068 ± 0.021*	22.23 ± 0.73*	25.82 ± 1.11*	72 ± 4*
	BM	0.011 ± 0.021*	0.012 ± 0.094*	21.29 ± 1.44*	21.82 ± 1.44*	64 ± 19*
Amateur	SB	0.029 ± 0.018*	0.029 ± 0.014*	24.48 ± 0.62*	21.60 ± 1.46*	71 ± 4*
	BM	0.012 ± 0.025*	0.070 ± 0.104*	22.07 ± 1.26*	20.93 ± 1.26*	73 ± 22*

Note: * denotes a significant difference ($p < 0.05$) between delivery methods.

As with the forward drive trials, although no significant effect was found for skill level group in terms of shot outcome, further visual inspection of the data revealed some interesting trends. Again the difference in variability in impact location between delivery methods is evident. There is however, some graphical evidence of increased variability in impact location for the amateur group in both the medio-lateral and vertical planes of the bat when facing the bowling machine (Figure 7.5). A similar trend is found when examining post-impact direction, with the elite group seeming to be less variable when facing the bowling machine (Figure 7.6), although again this is non-significant. Interestingly, variability in post-impact ball speed when facing the bowling machine seems to be very similar between groups (Figure 7.6), while the elite group seem to display a marked increase in variability in bat speed against the bowling machine (Figure 7.7).

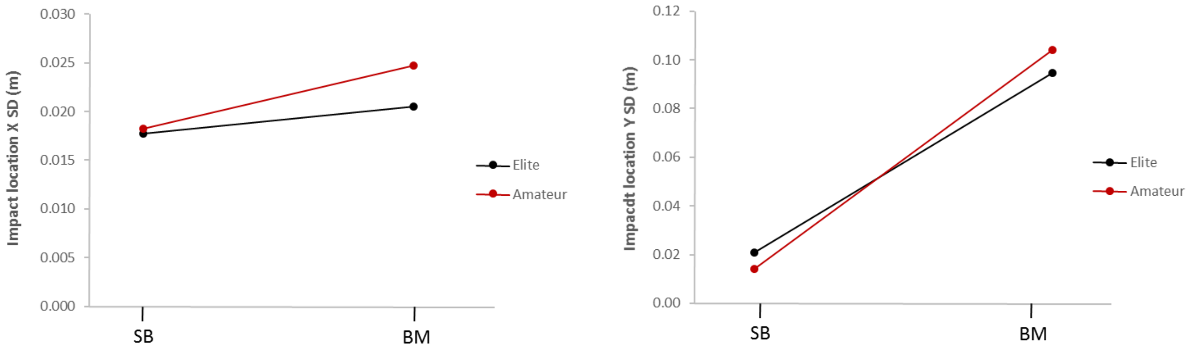


Figure 7.5: Variability (SD) in impact location of in the medio-lateral (X) and vertical (Z) planes from the sweetspot for elite and amateur groups in the static ball (SB) and bowling machine (BM) pull shots.

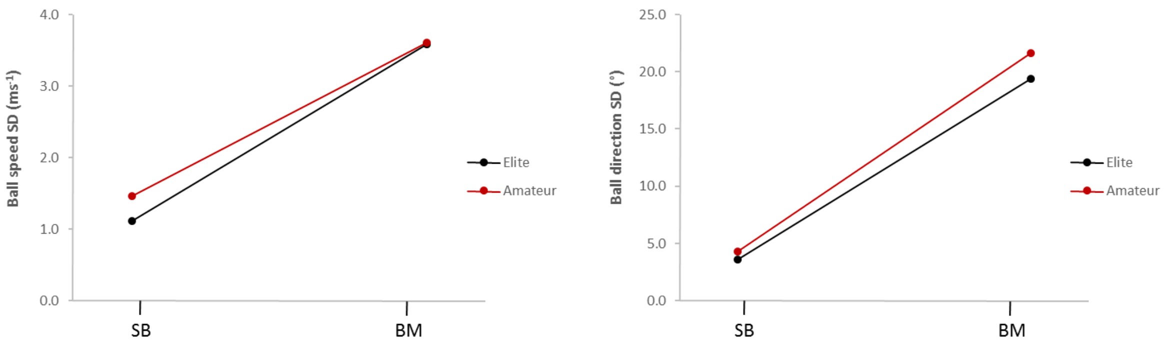


Figure 7.6: Variability (SD) in post-impact ball speed and direction for elite and amateur groups in the static ball (SB) and bowling machine (BM) pull shots.

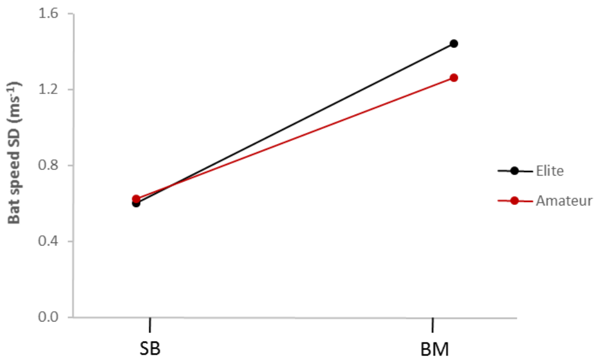


Figure 7.7: Variability (SD) in bat speed for elite and amateur groups in the static ball (SB) and bowling machine (BM) pull shots.

7.3.2.3 Movement Timings

Repeated measures MANOVA revealed a significant multivariate effect for delivery method ($V = 0.883$, $F(4, 12) = 22.55$, $p < 0.001$) and skill level group ($V = 0.723$, $F(4, 12) = 7.85$, $p < 0.01$) in terms of variability in movement timing variables. No significant effect was found for the interaction between delivery method and group. Within group univariate analyses indicated that the timing of the backwards transfer of weight ($F(1, 15) = 18.66$, $p < 0.01$), commencement of the downswing ($F(1, 15) = 44.94$, $p < 0.001$), and forwards motion of the hands during the downswing ($F(1, 15) = 87.78$, $p < 0.001$) events were all significantly less variable in the static ball trials than the bowling machine trials (Table 7.6). A trend ($p < 0.10$) also suggested a similar pattern when considering the commencement of the backswing.

Univariate between groups analyses showed that the amateur group were significantly more variable in the timing of their backwards weight transfer than the elite group ($F(1, 15) = 7.83$, $p < 0.05$; Figure 7.8). As in the forward drive, the timing of the start of the downswing, in both static ball and bowling machine conditions, was again the most consistent and therefore least variable event, displaying temporal variability of just 0.010 s and 0.019 s respectively.

Table 7.6: Movement timing variables for the static ball (SB) and bowling machine (BM) pull shots (mean ± SD).

Group	Delivery Method	BS start (s)	COM back (s)	DS start (s)	Hands fwd. (s)
Elite	SB	0.498 ± 0.027	0.231 ± 0.023*	0.204 ± 0.009*	0.241 ± 0.009*
	BM	0.466 ± 0.029	0.370 ± 0.033*	0.214 ± 0.018*	0.226 ± 0.019*
Amateur	SB	0.590 ± 0.025	0.411 ± 0.026*	0.227 ± 0.012*	0.243 ± 0.011*
	BM	0.444 ± 0.030	0.476 ± 0.048*	0.209 ± 0.019*	0.209 ± 0.020*

Note: * denotes a significant difference ($p < 0.05$) between delivery methods.

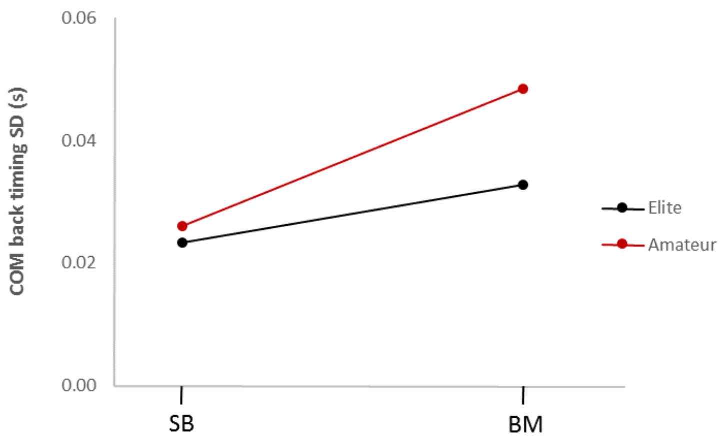


Figure 7.8: Variability (SD) in the timing of the COM back event for elite and amateur groups in the static ball (SB) and bowling machine (BM) pull shots.

7.3.2.4 Kinematics

Visual inspection of the variability data for bat angle (Figure 7.9) revealed several interesting trends. As was found in the forward drive, it is evident that while bat angle variability decreased throughout the shot towards impact in the static ball trials, variability in the bowling machine trials was found to stay relatively consistent up until the commencement of the downswing, then increase rapidly up to the point of impact.

In each case there are only minor differences between the elite and amateur groups in terms of measured variability when hitting a static ball or against a bowling machine, with the amateur group perhaps displaying more variability particularly throughout the static ball trials. Finally, the absolute measured variability in bat angle at the point of impact in the bowling machine trials was markedly higher for the pull shot, reaching standard deviation values of 17° in comparison to the 9° measured during the forward drive.

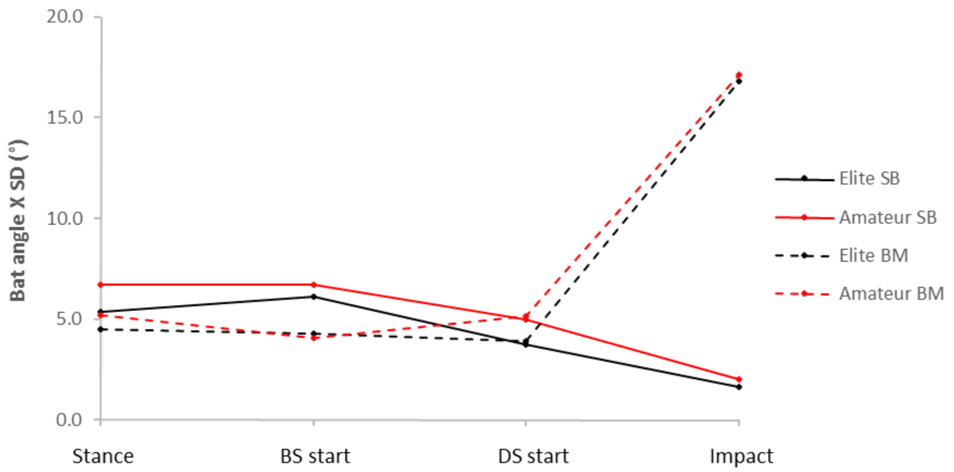


Figure 7.9: Variability (SD) in bat angle X at key time intervals throughout the static ball (SB) and bowling machine (BM) pull shots.

Examination of the variability data for wrist cocking angle, front elbow angle, and back elbow angle (Figure 7.10), reveals similar trends to the bat angle assessment. For both the front and back elbow angles, variability in the static ball trials remained relatively consistent throughout, perhaps displaying a slight reduction in variability at the commencement of the downswing relative to the other events. As in the bat angle assessment, measured variability in the front and back elbow angles was found to dramatically increase between the commencement of the downswing and the time of impact for both skill level groups, with the amateurs perhaps displaying slightly more variability than the elite players. Interestingly, absolute variability in the wrist cocking angle was around half that found in both the front and back elbow angles, suggesting relatively low variability in this variable. The amateur group, however, were found to show a large increase in wrist cocking angle variability between the commencement of the downswing and the time of impact for both the bowling machine and static ball trials. Only minor differences are evident between the two skill groups, suggesting similar patterns of variability between the two in these situations.

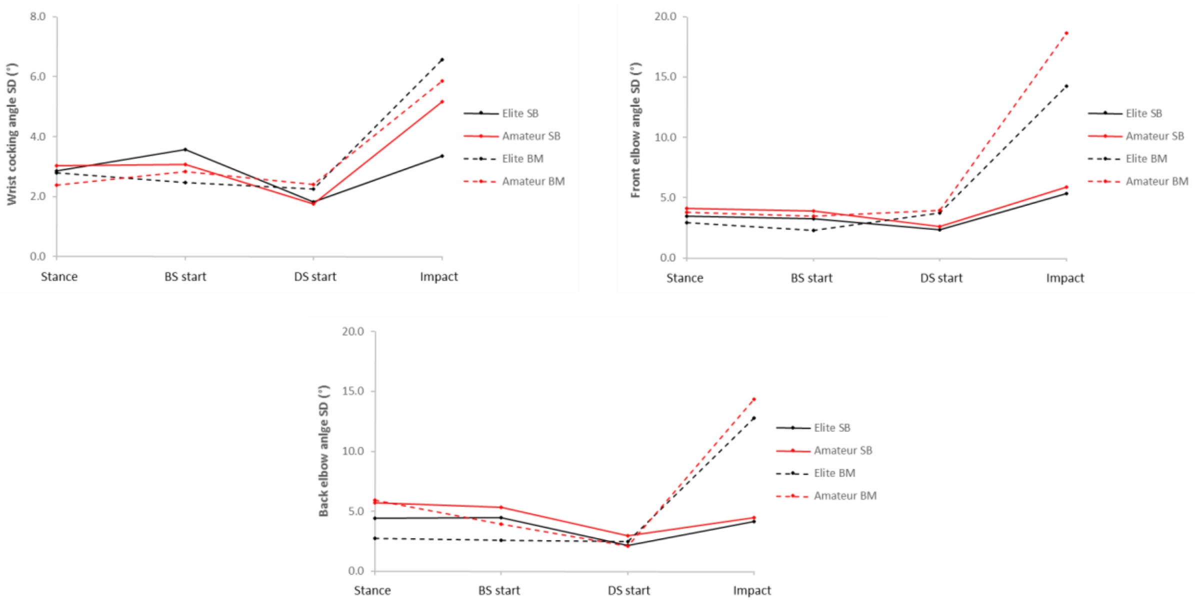


Figure 7.10: Variability (SD) in wrist cocking angle, front elbow angle X, and back elbow angle X at key time intervals throughout the static ball (SB) and bowling machine (BM) pull shots.

7.4 Discussion

The purpose of this study was to examine movement variability in the forward drive and pull shot for both elite and amateur batsmen under two separate conditions; hitting a static ball off a batting tee, and hitting against a bowling machine. A number of differences in terms of delivery characteristics, shot outcome, and movement timings, particularly between delivery methods, have been identified throughout the analysis. Examination of variability data for four kinematic variables has also been carried out considering four kinematic variables.

Results showed the static ball trials to be significantly less variable in terms of ball position at the time of impact than the bowling machine trials in the global medio-lateral (X), anterior-posterior (Y), and vertical (Z) planes, for both the forward drive and pull shots. There were however, no differences found in terms of variability in ball position between skill level groups or the interaction between delivery method and group. As expected, the ball was positioned very consistently for the static ball trials, while the bowling machine failed to replicate the same level of consistency across either shot type. This increased variability in ball delivery during the bowling machine trials must be taken into account when examining variability in shot outcome, movement timings, and kinematics, as it is a likely cause of variability in response for any given batsman either across their range of bowling machine trials, or in comparison of the two trial types. The fact that no differences were found in terms of variability in ball position at impact between skill level groups, indicates that for each delivery method any further observed differences in variability between groups cannot be attributed to the ball delivery, and therefore must be a factor of the expertise of the players.

Similarly, analysis of variability in shot outcome for both the forward drive and pull shots found static ball trials to be significantly less variable than bowling machine trials across all variables assessed. It seems likely that the stationary nature of the ball in the static ball trials makes the task of interception substantially easier for batsmen in both the amateur and elite groups, allowing them to achieve a more consistent impact location and bat speed, as well as post-impact ball speed and direction. It is likely that the increased difficulty experienced by having to intercept a moving ball, along with the significantly greater variability in ball delivery in the bowling machine trials, was a direct cause of the increased measured variability in shot outcome. The nature of intercepting a moving ball with higher variability in delivery characteristics also suggests that, while they may have a particular outcome in terms of ball speed and direction in mind as the ball is delivered, the changing inbound characteristics may force them to change their shot, and thus the outcome they achieve.

Although no significant differences were found between the elite and amateur groups in terms of shot outcome, it is suggested in the results that some trends are emerging in the data. Visual inspection of the data suggests that the amateur group may exhibit increased variability in terms of impact location, particularly in the bowling machine trials, with the elite group displaying lower variability in their impact location in the vertical plane of the bat during the forward drives, and in both the medio-lateral and vertical planes of the bat in the pull shots. This was an expected outcome of the study, as due to their increased expertise, elite players were expected to generate not only more accurate but also more consistent impact locations near the sweetspot of the bat. It is possible that, due to the repeatable nature of both the static ball and bowling machine trials when compared to facing a bowler, and the relative skill of five out of the seven amateur batsmen through premiership club cricket, the true difference in interception expertise was somewhat masked. Future studies investigating the impact of expertise on impact location should therefore consider a more variable and realistic ball delivery method, and with larger subject groups.

Results also suggested that the elite batsmen may have been less variable, and therefore more consistent, in terms of post-impact ball direction as also suggested by Weissensteiner et al. (2011). Although non-significant, this outcome was again expected, as the increased expertise of the elite group is thought to allow them to more easily place the ball into gaps in the field during their innings. While a target of hitting forward drives straight back past the bowler's end stumps, and pull shots just in front of square on the leg-side, was set for each batsman, the increased variability of the delivery of the bowling machine made this unrealistic and near impossible in some trials. Although this variability in delivery was equal between the two skill level groups, it is perhaps one reason why the expertise of the elite group was not shown in this study. Perhaps future studies investigating post-impact ball direction and placement between the fielders should set multiple targets for the batsmen to aim at dependent on the line and length of the particular delivery in question.

Initial inspection of the movement timing results, revealed that when playing the forward drive batsmen were more variable in the timings of the commencement and completion of their forward stride when facing the bowling machine than the static ball. This could be attributed to the highly repeatable nature of hitting in the static ball trials allowing a batsman to reproduce movements exactly, compared to the more variable bowling machine deliveries requiring more kinematic adjustment. In this case however, the variability of the start of backswing and start of downswing events remained equal between delivery methods. In particular, the absolute measured variability in the timing of the downswing for both skill level groups, against both delivery methods, was remarkably consistent. These findings, which are in agreement with the work of Weissensteiner et al. (2011), suggest that irrelevant of the skill level of the player or the ball delivery method used, when playing the forward drive batsmen place a priority on maintaining accurate timing of their bat swing, perhaps using feedback control to alter their stride and other movements during the shot in order to achieve this consistency.

Analysis of the pull shot data indicates that the timing of the backwards transfer of weight, commencement of downswing, and forwards motion of the hands during the downswing phase events were all significantly less variable in the static ball trials than the bowling machine trials. This can again be attributed to the highly repeatable nature of hitting a stationary ball off a batting tee compared to the more variable bowling machine deliveries. Again in the pull shot the timing of the commencement of the downswing showed the lowest variability of all defined events, suggesting that, similarly to the forward drive, batsmen focus on maintaining a consistent downswing perhaps by altering the timings and magnitudes of other movements. Interestingly, the elite group were also found to be significantly less variable in the timing of their backwards weight transfer than the amateur group, with the difference particularly evident in the bowling machine trials. This suggests that the elite group are perhaps more stable in their movement patterns for the pull shot, and thus more able to accurately coordinate their gross body movements with the delivery of the bowling machine balls.

Finally, inspection of upper limb and bat angle variability data revealed similar trends across both the forward drive and pull shots. In general, while measured variability in the static ball trials decreased from the stance phase through to the time of impact, variability in the bowling machine trials remained relatively consistent or decreased until the commencement of the downswing, before increasing dramatically in the approach to impact. The fact that kinematic variability in the static ball trials decreases through to impact is not a surprise. Hitting a stationary ball positioned in a consistent manner provides a substantially lower interceptive challenge, thus allows batsmen to reproduce movement patterns as accurately as they can, with a real focus on precision of movement. Hitting against the more variable bowling machine deliveries however, is a more realistic and challenging interceptive task, and thus requires flexibility in movement and hitting technique in order to maintain a successful impact and shot outcome. It is suggested that against the bowling machine, players exhibit stable movement patterns in their bat and upper limbs up until around the commencement of their downswing, hence the very low variability at this stage, before making adjustments to their body position and swing during the downswing phase in order to successfully intercept the ball. Whether these adjustments occur in real time throughout the downswing or are decided based on a prediction of ball arrival time and position around the commencement of the downswing, is currently unclear. Of course it could be argued that the variability in joint angles and bat angles at the time of impact is simply a result of players mistiming each shot thus reaching impact in different body positions, however as all these trials were qualified as successful with the ball being impacted strongly along the ground and approximately towards the target area, that explanation is unlikely. As a result it is likely this increase in upper limb and bat angle variability is evidence of batsmen exhibiting a prospective control mechanism, whereby adjustments to movement are made in an online manner based on up-to-date visual information.

Very few differences between skill level groups were evident from the kinematic data in both the forward drive and pull shots. In general, although only subtle in some cases, the amateur group displayed slightly more variability throughout the static ball trials than the elite group. This suggests that the elite batsmen have more stable movement patterns than the amateur group, perhaps as a result of their increased expertise through practice of each batting shot.

During the forward drive, the measured variability of the amateur group for bat angle and back elbow angle was substantially higher during the stance phase and at the commencement of the backswing, before reaching a similar level at the commencement of the downswing and at the time of impact. Although this does indicate a slightly less stable movement pattern, it is also evident from the similar kinematic and shot outcome variability measures between groups at the time of impact, that this had little to no effect on eventual performance. Evidence from throughout the kinematic data suggests that measured variability was lowest at the commencement of the downswing. Given that all the trials included in this study were deemed successful in terms of the quality of impact and having an appropriate post-impact speed and direction, and the remarkable consistency with which players time the commencement of their downswing, it is clear that batsmen and coaches should focus on this as a critical time in each batting shot. Batsmen should attempt to generate stable movement patterns up to this point, providing themselves with a solid base from which to adapt their shot to the changing perturbations of the forthcoming delivery. Future studies should consider using additional subjects to explore a wider range of kinematic variables, perhaps assessing variability on a continuous scale rather than simply at key time intervals throughout the shot.

7.5 Conclusions and Application to Coaching

This study has investigated the presence of movement variability amongst elite and amateur batsmen when hitting forward drives and pull shots both off a batting tee and against a bowling machine. Differences in variability between the two conditions have been quantified in terms of ball position at impact, shot outcome, and movement timings. Players were found to be in general far more consistent in their movement timings and shot outcome when hitting a stationary ball than a moving delivery from the bowling machine. This has been largely attributed to the increased task complexity and variability present in ball delivery and position at impact. Elite players were also suggested to be somewhat more consistent in their ability to generate consistent shot outcomes, although the non-significance of these differences may have been masked by the relatively repeatable nature of the delivery methods included in the study, and the low number of subjects in each group.

Variability in the kinematics of the bat and upper limbs has also been investigated via visual inspection of data. While players were found to constantly reduce kinematic variability throughout the static ball trials, variability in the bowling machine trials was found to increase dramatically during the downswing phase towards impact. While very few differences have been identified between the skill level groups, the commencement of the downswing has been identified as a critical time during the execution of each shot. It is recommended that batsmen attempt to generate stable movement patterns and body positions up to this point, giving them a solid base from which to adapt their movement patterns and hitting technique to their perception of the upcoming delivery in order to gain a successful impact and shot outcome. Further studies may investigate data from a single player or small group in a case study approach, investigating within subject variability as opposed to the variability between two groups. This would allow researchers and coaches to examine only those players with the best and most consistent shot outcomes, and better identify those aspects of technique defining successful performance.

CHAPTER 8

THE EFFECTS OF FACING DIFFERENT DELIVERY METHODS ON BATSMAN RESPONSE

8.1 Introduction

Elite cricket batsmen are highly attuned to a number of sources of information that aid in shot selection (section 2.3.1). By identifying these visual cues, elite batsmen can perceive pre-flight information regarding the future trajectory of the ball, allowing them to begin their movements before ball release (Müller et al., 2006). Due to the temporal and spatial difficulty of identifying ball arrival position and time against an elite fast bowler, this anticipatory skill is seen as essential for batting success (Müller et al., 2009). Indeed, as described in section 2.3.1.1, a number of studies have identified a relationship between skill level and anticipation, suggesting that elite sportspeople gain more information about future ball direction from pre-flight cues than lesser skilled players (Shim et al., 2005; Müller et al., 2006; Mann et al., 2010).

The majority of this pre-flight information is gained from visual cues during the bowler's delivery (section 2.3.1.2). However, many of these cues are not available when facing a bowling machine or Sidearm ball thrower. As a result, players rely on other cues such as the angle of the bowling machine head and information from early ball flight to time and organise their movements. It is thought that these cues are far less useful than those gained from the kinematics of a bowler's delivery, and as such a different technical response is exhibited (Pinder et al., 2011b).

Although several studies have investigated the effects of batting against a bowling machine compared to a bowler (Gibson & Adams, 1989; Renshaw et al., 2007; Cork et al., 2010; Pinder et al., 2009; 2011a), no consensus has yet been formed regarding the specific kinematic or movement timing differences, with results often being found to be contradictory to each other (section 2.3.1.3). Moreover, studies have all been carried out using video cameras alongside the batsman sampling at 100 Hz or below, which is likely to introduce errors in landmark identification and accurate event identification, and often using only a single subject or small sample (e.g. n=4) of players ranging in ability from club and development standard to international batsmen. This makes generalisation of the findings to the rest of the population difficult. Finally, the ball speed is relatively low in all cases (27-33 ms^{-1}), and no consideration is given to back foot shots which make up a large proportion of the options available to a batsman. As such, the aim of this study was to use a three-dimensional motion capture system to determine differences in delivery characteristics and the resulting kinematic response of a group of elite cricket batsmen when facing a bowling machine and a Sidearm ball thrower compared to when facing a bowler.

8.2 Methodology

8.2.1 Subjects

Nineteen cricket batsmen (mean ± SD: age = 21.6 ± 2.8 years; height = 1.82 ± 0.04 m; mass = 82.0 ± 8.2 kg) participated in this investigation. Subjects included one batsman with full international playing honours, five from the England Lions squad, one county player, eight that had represented England under 19's, and four premiership club batsmen. Due to some logistical issues and insufficient trial numbers for certain subjects, three batsmen had to be removed from the analysis of the forward drives (subjects 3, 17, and 21) and pull shots (subjects 3, 5, and 6) respectively, leaving a group of sixteen subjects for each. Six different right-arm fast bowlers of a similar playing level to each batting subject were used across the testing protocol, such that ball speeds would be realistic to a match scenario and appropriate for each batsman. Any significant differences in bowling speeds between the bowlers used would be measured and accounted for in later analyses.

8.2.2 Data Collection and Processing

Each batsman faced a series of deliveries from three different delivery methods; a bowling machine (n = 24), a Sidearm ball thrower (n = 40), and a bowler (n = 20). This generated four separate conditions according to the delivery method and pre-release knowledge of ball length; bowling machine with known length, Sidearm with known length, Sidearm with unknown length, and bowler with unknown length, as described in section 3.9.2. Deliveries were aimed such that batsmen could play a forward drive to half the deliveries of each type, and a pull shot to the other half. However, due to the inaccuracy of some of the delivery methods used in this testing, and the ability of the batsman to choose between multiple batting shots each time, not all deliveries were deemed suitable for the shot intended. As such only those trials where the intended shot was played by the batsmen, whether in a known or unknown condition, were taken forward for processing. Batsmen were encouraged at each stage to perform their shots as they would in a match environment. Each batting shot was captured by an 18 camera Vicon motion analysis system and three high-speed video cameras, all operating at 250 Hz as outlined in section 3.7. Sixty-two retro reflective markers were positioned on the body, bat, ball, and stumps (section 3.6). Trials were then reconstructed, manually labelled and filtered (section 4.3), before a biomechanical model was applied (section 4.4) and a series of key events automatically identified for each shot type (section 4.5.2).

8.2.3 Data Reduction

Only trials where a successful impact between the bat and ball, according to the scale proposed by Weissensteiner et al. (2009), were selected for analysis (bowling machine [BM] n = 9.4 ± 1.4 drives, 9.7 ± 1.8 pulls; Sidearm known [SA_K] n = 3.4 ± 0.8 drives, 5.8 ± 1.8 pulls; Sidearm unknown [SA_U] n = 3.7 ± 1.3 drives, 3.1 ± 1.1 pulls; and bowler [B] n = 3.4 ± 0.8 drives, 2.8 ± 1.2 pulls). A series of distinct timing and kinematic variables were then extracted from the biomechanical model for the forward drive and pull shots (a subset of those presented and defined in section 4.5.3) and taken forward into statistical analysis. As described in section 5.2, the commencement of the backswing of a single subject (subject 7) was found to occur considerably before ball release and thus had a substantial effect on the overall mean and standard deviation values for this event and any related movement durations. As such this subject’s data was removed from assessment of these measures.

8.2.4 Statistical Analysis

All statistical analysis was performed within SPSS v.22 (SPSS Corporation, USA). Separate one-way within-subjects’ ANOVAs ($p < 0.05$) were used to analyse each dependent variable. In cases where the sphericity assumption was violated, a Greenhouse-Geisser correction was used to adjust the degrees of freedom of the repeated variables in the ANOVAs. Post-hoc pairwise comparisons, with Bonferroni corrections to reduce the risk of type 1 errors in multiple comparisons, were then carried out to assess significant differences between individual delivery methods.

8.3 Results

Results are presented for the forward drive and pull shots in three distinct categories; delivery characteristics, movement timings and durations, and kinematics throughout each stage of the batting shot.

8.3.1 Forward Drives

8.3.1.1 Delivery Characteristics

One-way within-subjects' analyses revealed some significant differences between delivery methods in terms of delivery characteristics (Table 8.1). Ball speed was found to be significantly different between all three delivery method conditions and the bowlers ($F(1.35, 20.19) = 274.48$, $p < 0.001$), while the time between ball release and impact was also significantly different between the bowlers and both Sidearm conditions ($F(1.83, 27.48) = 43.68$, $p < 0.001$). This is indicative of a significantly faster ball speed in the bowling machine trials than the bowler trials, which in turn were significantly faster than the Sidearm trials. This resulted in the ball taking significantly longer to reach the batsman from the time of release when facing the Sidearm than the bowlers. Finally, analysis of the timing of ball bounce, measured as a percentage of total ball release to impact time and thus assumed to identify any changes in bounce length, revealed no significant differences between delivery methods. The timing of the ball release and ball bounce events and the differences between delivery methods can also be seen in Figure 8.1.

Table 8.1: Differences in delivery characteristics between delivery methods for the forward drive trials (mean ± SD).

Variable	B	BM (vs. B)	SA_K (vs. B)	SA_U (vs. B)
Release time (s)	0.547 ± 0.031	0.531 ± 0.048	0.607 ± 0.032*	0.611 ± 0.031*
Bounce time (s)	0.092 ± 0.027	0.080 ± 0.011	0.084 ± 0.019	0.088 ± 0.022
Ball speed (ms^{-1})	33.26 ± 0.64	35.30 ± 1.88*	27.68 ± 0.56*	28.21 ± 0.82*

Note: B = bowler, BM = bowling machine, SA_K = Sidearm known length, SA_U = Sidearm unknown length, * denotes a significant difference ($p < 0.05$).

8.3.1.2 Movement Timings and Durations

Analysis of the timing of key events within the forward drive (Table 8.2) revealed that while no significant differences were present between the bowler and the bowling machine trials, batsmen were found to begin their backswing ($F(3, 42) = 12.88$, $p < 0.001$) and forward stride ($F(1.42, 19.87) = 8.07$, $p < 0.05$) earlier relative to impact in both Sidearm conditions than when facing the bowlers. Subjects were also found to start their downswing earlier relative to impact when facing the Sidearm with a known length compared to the bowlers ($F(3, 42) = 6.67$, $p < 0.05$). No significant differences were found when assessing the timing of the end of the forward stride.

Table 8.2: Differences in movement timings between delivery methods for the forward drive trials (mean ± SD).

Variable	B	BM (vs. B)	SA_K (vs. B)	SA_U (vs. B)
BS start (s)	0.452 ± 0.052 [a]	0.440 ± 0.061 [a]	0.496 ± 0.082* [a]	0.482 ± 0.070* [a]
Stride start (s)	0.402 ± 0.099	0.412 ± 0.051	0.476 ± 0.063*	0.467 ± 0.060*
DS start (s)	0.177 ± 0.029	0.182 ± 0.032	0.198 ± 0.039*	0.186 ± 0.027
Stride end (s)	0.066 ± 0.025	0.061 ± 0.032	0.075 ± 0.033	0.082 ± 0.030

Note: B = bowler, BM = bowling machine, SA_K = Sidearm known length, SA_U = Sidearm unknown length, * denotes a significant difference ($p < 0.05$), [a] = data from subject 7 removed.

Assessment of the durations of key phases of movement within the forward drive (Table 8.3) displayed that players exhibited a significantly longer stride duration ($F(1.54, 21.61) = 5.34$, $p < 0.05$) and total movement time ($F(2.08, 29.13) = 10.59$, $p < 0.001$) when facing the Sidearm in both known and unknown conditions compared to the bowlers. Again no significant differences were found between the bowler and bowling machine conditions, or regarding movement initiation time and backswing duration.

Table 8.3: Differences in movement durations between delivery methods for the forward drive trials (mean ± SD).

Variable	B	BM (vs. B)	SA_K (vs. B)	SA_U (vs. B)
MIT (s)	0.090 ± 0.045 [a]	0.082 ± 0.061 [a]	0.098 ± 0.074 [a]	0.117 ± 0.056 [a]
Stride duration (s)	0.336 ± 0.104	0.350 ± 0.063	0.402 ± 0.074*	0.384 ± 0.076*
BS duration (s)	0.276 ± 0.046 [a]	0.260 ± 0.056 [a]	0.299 ± 0.068 [a]	0.297 ± 0.066 [a]
Movement time (s)	0.459 ± 0.055 [a]	0.453 ± 0.058 [a]	0.510 ± 0.079* [a]	0.496 ± 0.068* [a]

Note: B = bowler, BM = bowling machine, SA_K = Sidearm known length, SA_U = Sidearm unknown length, * denotes a significant difference ($p < 0.05$), [a] = data from subject 7 removed.

The timings and durations of key events and phases of the forward drive, and the differences between delivery methods, can also be seen in Figure 8.1.

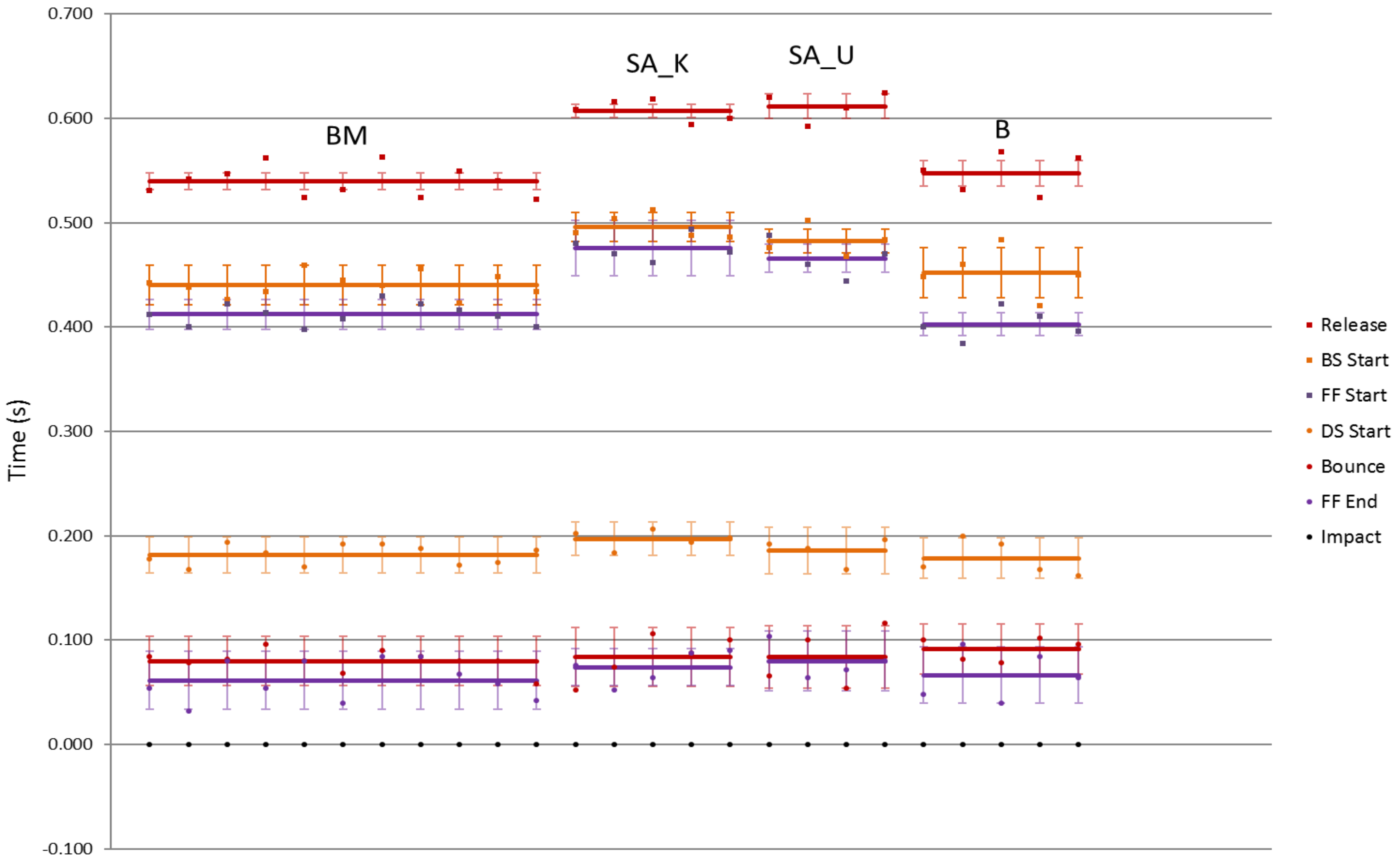


Figure 8.1: The timings of key events in the forward drive relative to the moment of impact for an example subject.

Note: BM = bowling machine, SA_K = Sidearm known length, SA_U = Sidearm unknown length, B = bowler. Each column represents a single trial, with the delivery method average and standard deviation shown by the solid line and error bars respectively.

8.3.1.3 Kinematics

Analysis of kinematic measures revealed a number of significant differences within the stance phase of the forward drive (Table 8.4). Batsmen were found to position their centre of mass ($F(1.89, 28.35) = 11.52$, $p < 0.001$), front shoulder ($F(1.52, 22.85) = 13.04$, $p < 0.001$), and head ($F(1.58, 23.82) = 14.51$, $p < 0.001$), further forward towards the front foot at the point of ball release when facing the bowling machine compared to the bowler. Similarly, a trend ($p < 0.10$) also suggested the front knee was positioned further forwards towards the front foot at ball release.

Results also indicated that players exhibited a significantly straighter back knee during the stance phase when facing the Sidearm in both the known and unknown length conditions compared to the bowlers ($F(1.94, 29.02) = 6.79$, $p < 0.01$), resulting in a higher centre of mass relative to the lab floor at the point of ball release ($F(3, 45) = 8.34$, $p < 0.001$). Batsmen were found to exhibit additional forward flexion in the thorax segment at the point of ball release when facing the bowlers compared to the Sidearm ($F(3, 45) = 8.89$, $p < 0.001$), with a trend ($p < 0.10$) suggesting a similar pattern when facing the bowling machine. Finally, the angle of the bat about the global medio-lateral axis was found to be higher at the point of ball release when facing the Sidearm than the bowlers ($F(1.89, 28.36) = 4.53$, $p < 0.05$), with the bat also found to be angled further towards the off-side about the global vertical axis when facing the bowlers than the Sidearm in the known length condition ($F(3, 45) = 3.61$, $p < 0.05$).

Assessment of kinematic measures at the top of the backswing (Table 8.5) revealed that batsmen exhibited a lower maximum bat angle about the global anterior-posterior axis ($F(2.21, 33.12) = 7.92$, $p < 0.01$), being indicative of a straighter backswing more over the stumps rather than towards the slips, as well as a significantly lower degree of extension ($F(2.08, 31.21) = 48.34$, $p < 0.001$) and adduction ($F(1.77, 26.55) = 20.32$, $p < 0.001$) at the back shoulder when facing the bowling machine compared to the bowlers. Trends ($p < 0.10$) also suggested players displayed a more front-on thorax and forward flexed pelvis at the top of the backswing when facing the bowling machine compared to the bowlers.

Table 8.4: Differences in stance phase kinematics between delivery methods for the forward drive trials (mean ± SD).

Variable	B	BM (vs. B)	SA_K (vs. B)	SA_U (vs. B)
Stance width (m)	0.527 ± 0.098	0.523 ± 0.083	0.528 ± 0.082	0.532 ± 0.079
COM position (% of base)	57 ± 9	64 ± 7*	60 ± 7	57 ± 6
F shoulder position Y relative to FF (m)	-0.051 ± 0.082	0.014 ± 0.062*	-0.021 ± 0.062	-0.047 ± 0.066
F knee position Y relative to FF (m)	-0.021 ± 0.049	0.010 ± 0.026**	-0.008 ± 0.033	-0.021 ± 0.032
Head position Y relative to FF (m)	-0.057 ± 0.078	0.008 ± 0.065*	-0.031 ± 0.057	-0.057 ± 0.061
Head position X relative to middle stump (m)	0.089 ± 0.082	0.080 ± 0.104	0.081 ± 0.097	0.080 ± 0.102
Front knee angle X (°)	140 ± 11	137 ± 7	141 ± 8	142 ± 8
Back knee angle X (°)	137 ± 8	141 ± 7	142 ± 8*	141 ± 9*
COM height (m)	0.963 ± 0.039	0.973 ± 0.041	0.979 ± 0.041*	0.980 ± 0.039*
Pelvis angle Z (°)	69 ± 7	69 ± 6	70 ± 6	70 ± 6
Thorax angle Z (°)	69 ± 4	68 ± 5	69 ± 4	69 ± 4
Thorax angle X (°)	-40 ± 9	-38 ± 9**	-38 ± 8*	-37 ± 10*
Thorax angle Y (°)	-3 ± 4	-2 ± 5*	-2 ± 5	-2 ± 5
Bat angle X (°)	-108 ± 22	-114 ± 25	-114 ± 22*	-114 ± 22*
Bat angle Y (°)	-15 ± 12	-13 ± 12	-12 ± 13*	-13 ± 14

Note: B = bowler, BM = bowling machine, SA_K = Sidearm known length, SA_U = Sidearm unknown length, * denotes a significant difference ($p < 0.05$), ** denotes a significant trend ($p < 0.10$).

When batting against the Sidearm in both known and unknown length conditions batsmen were found to display additional forward flexion of the pelvis ($F(3, 45) = 7.92$, $p < 0.001$), and lateral flexion of the thorax segment towards the bowler ($F(3, 45) = 9.81$, $p < 0.001$), at the top of the backswing compared to when facing the bowlers. Players were also found to lift their bottom wrist significantly higher at the top of the backswing ($F(3,45) = 3.21$, $p < 0.05$) when facing the Sidearm in the known length condition compared to when facing the bowlers.

Table 8.5: Differences in kinematics at the top of the backswing between delivery methods for the forward drive trials (mean ± SD).

Variable	B	BM (vs. B)	SA_K (vs. B)	SA_U (vs. B)
Bat angle X (°)	-146 ± 14	-147 ± 12	-150 ± 13	-151 ± 13
Max bat angle Y BS (°)	-21 ± 11	-17 ± 11*	-20 ± 11	-21 ± 11
Bat angle Y (°)	-7 ± 10	-9 ± 7	-9 ± 9	-8 ± 9
Bat COM height (m)	1.122 ± 0.101	1.134 ± 0.106	1.147 ± 0.085	1.151 ± 0.094
Wrist cocking angle (°)	122 ± 9	121 ± 5	122 ± 9	121 ± 8
Top wrist height (m)	0.879 ± 0.073	0.881 ± 0.070	0.885 ± 0.065	0.888 ± 0.065
Bottom wrist height (m)	1.019 ± 0.084	1.041 ± 0.091	1.044 ± 0.082*	1.038 ± 0.079
Front elbow angle X (°)	112 ± 11	110 ± 11	113 ± 10	114 ± 10
Back elbow angle X (°)	59 ± 6	58 ± 9	59 ± 7	60 ± 7
Front shoulder angle X (°)	50 ± 9	49 ± 9	49 ± 8	49 ± 7
Front shoulder angle Y (°)	-12 ± 10	-8 ± 9	-13 ± 7	-14 ± 9
Back shoulder angle X (°)	-34 ± 12	-16 ± 12*	-39 ± 13	-36 ± 14
Back shoulder angle Y (°)	-34 ± 11	-24 ± 9*	-34 ± 11	-34 ± 8
Pelvis angle Z (°)	57 ± 6	56 ± 8	57 ± 6	58 ± 6
Thorax angle Z (°)	68 ± 6	65 ± 6**	67 ± 6	68 ± 6
Z-factor (°)	11 ± 4	9 ± 4	10 ± 4	10 ± 4
Pelvis angle X (°)	-28 ± 9	-30 ± 8**	-31 ± 8*	-31 ± 9*
Thorax angle X (°)	-51 ± 6	-52 ± 6	-52 ± 5	-53 ± 7
X-factor (°)	24 ± 8	22 ± 7	22 ± 7	22 ± 7
Thorax angle Y (°)	-4 ± 5	-5 ± 5	-6 ± 5*	-6 ± 5*

Note: B = bowler, BM = bowling machine, SA_K = Sidearm known length, SA_U = Sidearm unknown length, * denotes a significant difference ($p < 0.05$), ** denotes a significant trend ($p < 0.10$).

Analysis of kinematic measures within the stride phase of the forward drive (Table 8.6) showed batsmen to utilise a longer forward stride ($F(1.92, 38.75) = 5.70$, $p < 0.01$) and therefore create a longer base at the end of the forward stride ($F(2.06, 20.87) = 6.67$, $p < 0.01$) when facing the Sidearm in the known length condition compared to the bowlers. A trend ($p < 0.10$) also suggested the base created at the end of the forward stride was longer against the Sidearm in the unknown length condition than when facing the bowlers.

In addition to the increased stride length, the whole body centre of mass ($F(1.76, 26.39) = 13.31$, $p < 0.001$) and head ($F(3, 45) = 15.91$, $p < 0.001$) were found to move further forward in the global anterior-posterior plane between the start of the forward stride and impact when facing the Sidearm in both the known and unknown length conditions compared to when facing the bowlers. Similarly, batsmen were also found to move their head further forward in the anterior-posterior plane between the start of the forward stride and impact when facing the bowling machine compared to the bowlers. Along with the increased forward movement of the head and centre of mass, players were found to exhibit significantly more downward movement of the whole body centre of mass ($F(2.08, 31.16) = 6.41$, $p < 0.01$) and head ($F(1.73, 26.00) = 9.35$, $p < 0.01$) in the global vertical plane between the commencement of the forward stride and impact when facing the Sidearm than the bowlers.

Table 8.6: Differences in forward stride phase kinematics between delivery methods for the forward drive trials (mean ± SD).

Variable	B	BM (vs. B)	SA_K (vs. B)	SA_U (vs. B)
Stride length (m)	0.323 ± 0.180	0.413 ± 0.109	0.450 ± 0.142*	0.386 ± 0.128
Base length (m)	0.810 ± 0.127	0.868 ± 0.097	0.916 ± 0.136*	0.883 ± 0.101**
COM position (% of base)	61 ± 5	62 ± 4	63 ± 4	61 ± 4
Thorax angle X (°)	-42 ± 10	-44 ± 9	-46 ± 7	-45 ± 10
Front knee angle X (°)	152 ± 11	153 ± 8	152 ± 8	152 ± 10
COM travel Y stride start to impact (m)	0.240 ± 0.107	0.296 ± 0.071	0.351 ± 0.102*	0.316 ± 0.076*
COM travel Z stride start to impact (m)	-0.025 ± 0.059	-0.051 ± 0.037	-0.068 ± 0.049*	-0.058 ± 0.048*
Head travel Y stride start to impact (m)	0.181 ± 0.114	0.270 ± 0.083*	0.320 ± 0.109*	0.277 ± 0.086*
Head travel Z stride start to impact (m)	-0.109 ± 0.096	-0.162 ± 0.070	-0.185 ± 0.075*	-0.171 ± 0.074*

Note: B = bowler, BM = bowling machine, SA_K = Sidearm known length, SA_U = Sidearm unknown length, * denotes a significant difference ($p < 0.05$), ** denotes a significant trend ($p < 0.10$).

Assessment of kinematic measures within the downswing phase of the forward drive (Table 8.7) revealed only one significant difference between delivery methods. Batsmen were found to exhibit significantly more back shoulder flexion during the downswing ($F(2.19, 32.82) = 6.64$, $p < 0.01$) when facing the Sidearm in the known length condition than the bowlers. A trend ($p < 0.10$) also suggested that players utilised a lower degree of front elbow extension during the downswing when facing the bowling machine than the bowlers.

Table 8.7: Differences in downswing kinematics between delivery methods for the forward drive trials (mean ± SD).

Variable	B	BM (vs. B)	SA_K (vs. B)	SA_U (vs. B)
Max bat speed (°s^{-1})	1437 ± 208	1392 ± 129	1366 ± 164	1490 ± 208
Max bat distal endpoint speed (ms^{-1})	20.09 ± 2.10	19.43 ± 1.27	20.11 ± 1.65	20.78 ± 1.81
Wrist uncocking (°)	35 ± 13	35 ± 8	36 ± 12	38 ± 12
Max X-factor (°)	24 ± 8	23 ± 7	23 ± 7	23 ± 7
Max Z-factor (°)	15 ± 4	14 ± 5	15 ± 4	16 ± 5
Front elbow extension (°)	21 ± 12	13 ± 10**	20 ± 11	18 ± 11
Back elbow extension (°)	48 ± 12	41 ± 9	49 ± 10	47 ± 11
Front shoulder rotation X (°)	35 ± 13	38 ± 10	39 ± 12	36 ± 11
Front shoulder rotation Y (°)	12 ± 8	14 ± 8	15 ± 8	14 ± 7
Back shoulder rotation X (°)	72 ± 13	71 ± 15	79 ± 16*	73 ± 15
Back shoulder rotation Y (°)	13 ± 9	14 ± 7	16 ± 10	14 ± 7

Note: B = bowler, BM = bowling machine, SA_K = Sidearm known length, SA_U = Sidearm unknown length, * denotes a significant difference ($p < 0.05$), ** denotes a significant trend.

Finally, analysis of kinematic measures at the time of impact (Table 8.8) showed that batsmen exhibited additional forwards flexion in the thorax segment ($F(3, 45) = 4.69$, $p < 0.01$), and greater forwards speed of the whole body centre of mass in the global anterior-posterior plane ($F(3, 45) = 6.52$, $p < 0.01$), when facing the bowling machine and the Sidearm in the known length condition compared to when facing the bowlers. Players were also found to display a longer base length at the point of impact ($F(3, 45) = 5.96$, $p < 0.01$) when facing the Sidearm in the known length condition compared to when facing the bowlers.

Table 8.8: Differences in kinematics at the point of impact between delivery methods for the forward drive trials (mean ± SD).

Variable	B	BM (vs. B)	SA_K (vs. B)	SA_U (vs. B)
Wrist cocking angle (°)	142 ± 13	144 ± 8	144 ± 11	145 ± 11
X-factor (°)	12 ± 10	14 ± 9	12 ± 10	12 ± 9
Z-factor (°)	4 ± 6	6 ± 5	5 ± 6	6 ± 7
Pelvis angle Z (°)	30 ± 6	29 ± 7	30 ± 8	28 ± 6
Thorax angle X (°)	-29 ± 11	-35 ± 11*	-33 ± 10*	-31 ± 12
Thorax angle Z (°)	34 ± 10	35 ± 9	35 ± 9	33 ± 9
COM height (m)	0.922 ± 0.054	0.911 ± 0.028	0.896 ± 0.045	0.903 ± 0.043
Base length (m)	0.784 ± 0.116	0.845 ± 0.091	0.882 ± 0.123*	0.847 ± 0.101
COM position (% of base)	66 ± 6	68 ± 4	69 ± 5	68 ± 6
COM speed Y (ms^{-1})	0.76 ± 0.22	0.90 ± 0.16*	0.91 ± 0.24*	0.88 ± 0.17
Front shoulder position Y relative to front foot (m)	-0.221 ± 0.086	-0.196 ± 0.075	-0.203 ± 0.076	-0.210 ± 0.083
Front knee position Y relative to front foot (m)	-0.037 ± 0.039	-0.054 ± 0.033	-0.034 ± 0.029	-0.032 ± 0.031
Head position Y relative to front foot (m)	-0.121 ± 0.091	-0.081 ± 0.097	-0.096 ± 0.091	-0.105 ± 0.103
Head position Z relative to front foot (m)	1.242 ± 0.066	1.219 ± 0.051	1.202 ± 0.055	1.211 ± 0.066
Front knee angle X (°)	151 ± 14	152 ± 10	146 ± 10	147 ± 10
Back knee angle X (°)	144 ± 18	150 ± 11	146 ± 15	146 ± 13
Bat angle X (°)	-22 ± 8	-24 ± 5	-19 ± 6	-20 ± 7
Bat COM position Y relative to front knee (m)	0.028 ± 0.120	0.036 ± 0.087	0.067 ± 0.089	0.051 ± 0.117
Bat COM position Y relative to head (m)	0.112 ± 0.098	0.063 ± 0.058	0.130 ± 0.082	0.123 ± 0.068

Note: B = bowler, BM = bowling machine, SA_K = Sidearm known length, SA_U = Sidearm unknown length, * denotes a significant difference ($p < 0.05$).

8.3.2 Pull Shots

8.3.2.1 Delivery Characteristics

Within-subjects' analyses of delivery characteristics (Table 8.9) revealed that, as with the forward drive trials, ball speed was faster in the bowling machine trials than the bowler trials, which were in turn faster than the Sidearm trials ($F(1.42, 21.24) = 290.00$, $p < 0.001$). This again resulted in a longer time from ball release to impact in the Sidearm trials than when facing the bowlers ($F(1.56, 23.38) = 42.976$, $p < 0.001$). Interestingly the ball was also found to bounce earlier relative to impact in both the Sidearm and bowling machine trials than the bowler trials ($F(3, 45) = 26.10$, $p < 0.001$). The timing of the ball release and ball bounce events and the differences between delivery methods can also be seen in Figure 8.2.

Table 8.9: Differences in delivery characteristics between delivery methods for the pull shot trials (mean ± SD).

Variable	B	BM (vs. B)	SA_K (vs. B)	SA_U (vs. B)
Release time (s)	0.573 ± 0.040	0.590 ± 0.051	0.660 ± 0.047*	0.646 ± 0.043*
Bounce time (s)	0.292 ± 0.031	0.322 ± 0.030*	0.369 ± 0.032*	0.355 ± 0.030*
Ball speed (ms^{-1})	33.26 ± 0.80	34.83 ± 1.60*	28.14 ± 0.46*	28.31 ± 0.43*

Note: B = bowler, BM = bowling machine, SA_K = Sidearm known length, SA_U = Sidearm unknown length, * denotes a significant difference ($p < 0.05$).

8.3.2.2 Movement Timings and Durations

Analysis of the timing of key events within the pull shot (Table 8.10) revealed that batsmen began their backswing significantly earlier relative to the time of impact when facing the bowlers than the bowling machine ($F(3, 42) = 17.56$, $p < 0.001$). Furthermore, there was a trend ($p < 0.10$) suggesting players began their backswing earlier relative to impact when facing the Sidearm in the unknown length condition than the bowler. Batsmen were also found to begin to transfer their centre of mass backwards in preparation for the downswing of the bat earlier relative to impact in the Sidearm trials with a known length than the bowler trials ($F(2.14, 29.96) = 6.25$, $p < 0.01$), with a trend ($p < 0.10$) suggesting a similar pattern between the Sidearm trials with an unknown length and the bowlers. No significant differences were found when assessing the timing of the start of the downswing between any of the delivery method conditions in this study.

Table 8.10: Differences in movement timings between delivery methods for the pull shot trials (mean ± SD).

Variable	B	BM (vs. B)	SA_K (vs. B)	SA_U (vs. B)
BS start (s)	0.480 ± 0.069 [a]	0.427 ± 0.061* [a]	0.494 ± 0.076 [a]	0.509 ± 0.097** [a]
COM back (s)	0.337 ± 0.058	0.402 ± 0.097	0.428 ± 0.072*	0.391 ± 0.071**
DS start (s)	0.222 ± 0.055	0.207 ± 0.026	0.227 ± 0.035	0.224 ± 0.035

Note: B = bowler, BM = bowling machine, SA_K = Sidearm known length, SA_U = Sidearm unknown length, * denotes a significant difference ($p < 0.05$), ** denotes a significant trend ($p < 0.10$), [a] = data from subject 7 removed.

Assessment of the durations of key phases of movement within the forward drive (Table 8.11) showed players to commence their first movement (MIT) significantly later relative to the time of ball release when facing the Sidearm in the known length condition than the bowlers ($F(3, 42) = 3.26$, $p < 0.05$). Batsmen were also found to exhibit a longer total movement time in the Sidearm unknown length condition than when facing the bowlers ($F(2.08, 29.10) = 5.98$, $p < 0.01$), and a trend ($P < 0.10$) suggested that players exhibited a shorter backswing duration against the bowling machine than the bowlers.

Table 8.11: Differences in movement durations between delivery methods for the pull shot trials (mean ± SD).

Variable	B	BM (vs. B)	SA_K (vs. B)	SA_U (vs. B)
MIT (s)	0.097 ± 0.060 [a]	0.134 ± 0.056 [a]	0.155 ± 0.073* [a]	0.129 ± 0.077 [a]
BS duration (s)	0.262 ± 0.070 [a]	0.222 ± 0.050** [a]	0.267 ± 0.070 [a]	0.287 ± 0.094 [a]
Movement time (s)	0.480 ± 0.069 [a]	0.459 ± 0.059 [a]	0.506 ± 0.076 [a]	0.519 ± 0.089* [a]

Note: B = bowler, BM = bowling machine, SA_K = Sidearm known length, SA_U = Sidearm unknown length, * denotes a significant difference ($p < 0.05$), ** denotes a significant trend ($p < 0.10$), [a] = data from subject 7 removed.

The timings and durations of key events and phases of the forward drive, and the differences between delivery methods, can also be seen in Figure 8.2.

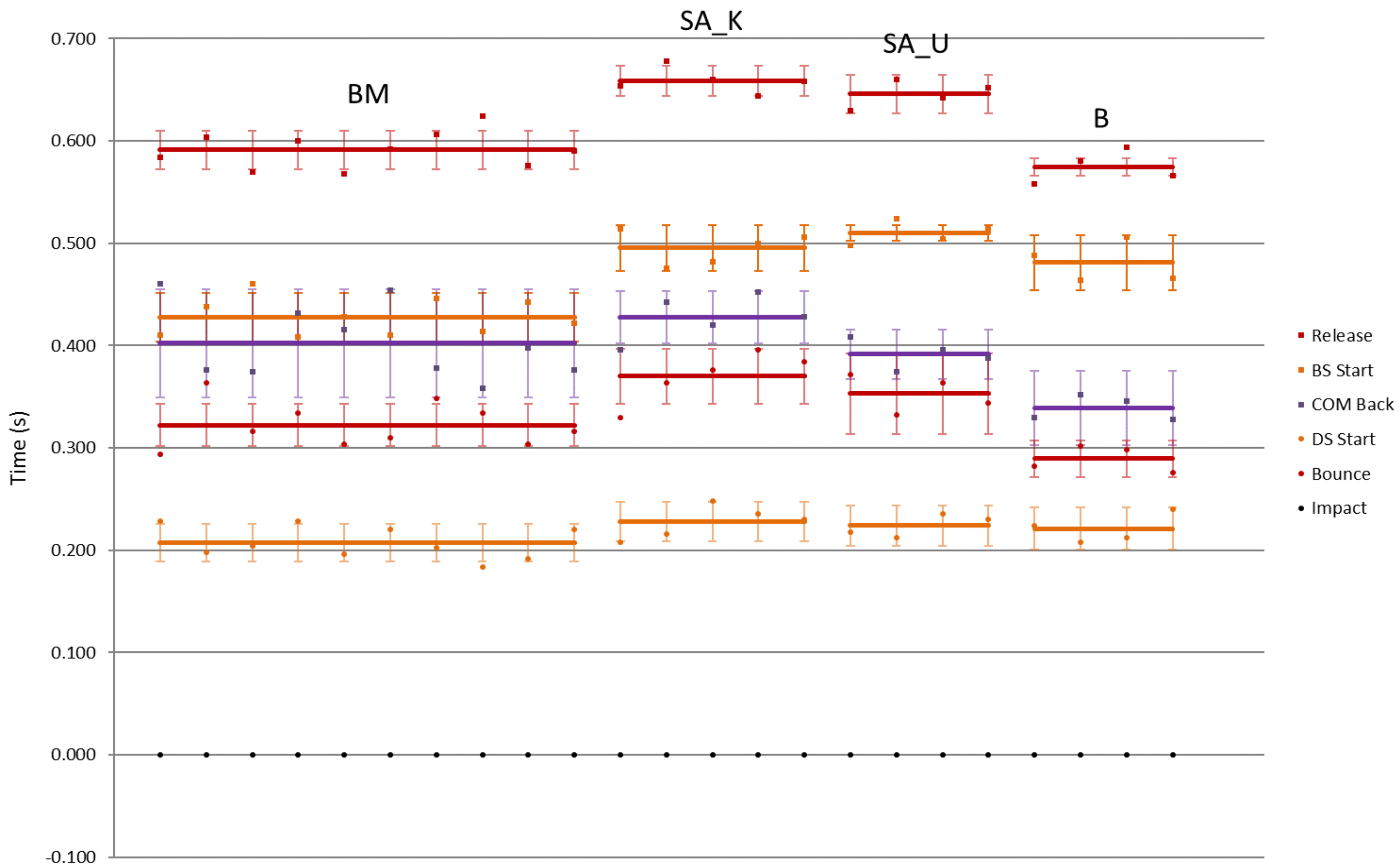


Figure 8.2: The timings of key events in the pull shot relative to the moment of impact for an example subject.

Note: BM = bowling machine, SA_K = Sidearm known length, SA_U = Sidearm unknown length, B = bowler. Each column represents a single trial, with the delivery method average and standard deviation shown by the solid line and error bars respectively.

8.3.2.3 Kinematics

Assessment of kinematic measures within the stance phase of the pull shot (Table 8.12) showed batsmen to exhibit a more extended back knee ($F(1.89, 28.28) = 10.72$, $p < 0.001$) and hip ($F(1.78, 26.68) = 6.96$, $p < 0.01$) at the moment of release when facing the Sidearm in both the known and unknown length conditions than when facing the bowlers. Batsmen also displayed a more extended back knee at the point of ball release when facing the bowling machine compared to the bowlers. Players were found to exhibit a lower degree of forward flexion ($F(1.75, 26.18) = 18.71$, $p < 0.001$) and lateral flexion towards the bowler's end ($F(1.06, 15.97) = 6.68$, $p < 0.05$) of the thorax segment when facing the bowling machine and Sidearm than when facing the bowlers. As a result of this the whole body centre of mass was found to be positioned higher above the pitch surface in the global vertical axis at the moment of ball release ($F(1.55, 23.19) = 8.05$, $p < 0.01$) when facing the Sidearm in both the known and unknown length conditions compared to when facing the bowlers.

Finally, the bat was found to be raised to a significantly higher angle about the global medio-lateral axis ($F(1.95, 29.29) = 7.46$, $p < 0.01$) at the moment of ball release when facing the bowling machine compared to the bowlers, and to exhibit a greater angle towards the off-side about the global anterior-posterior axis ($F(1.57, 23.53) = 6.46$, $p < 0.01$) when facing the Sidearm in the known length condition than when facing the bowlers.

Analysis of kinematic measures at the top of the backswing during the pull shot revealed a number of significant differences between delivery methods (Table 8.13). Batsmen were found to raise the bat centre of mass ($F(3,45) = 20.82$, $p < 0.001$), top wrist ($F(3, 45) = 22.79$, $p < 0.001$), and bottom wrist ($F(3, 45) = 22.41$, $p < 0.001$) higher above the pitch surface in the global vertical plane at the top of the backswing when facing the bowling machine and the Sidearm compared to the bowlers. The bat was also found to be raised to a significantly higher angle about the global medio-lateral axis ($F(3, 45) = 3.89$, $p < 0.05$) at the top of the backswing when facing the Sidearm in the known length condition than the bowlers, and exhibit an angle significantly more towards the leg-side about the global anterior-posterior axis ($F(3, 45) = 8.81$, $p < 0.001$) when facing the bowling machine and Sidearm in both length conditions, compared to when facing the bowlers the bat was found to be angled slightly towards the off-side. Interestingly, batsmen were also found to exhibit a greater maximum bat angle towards the off-side about the global anterior-posterior axis during the backswing (F(1.84, 27.62) = 6.64, $p < 0.05$) when facing the Sidearm in the known length condition, being indicative of a more looped backswing in this case.

Table 8.12: Differences in stance phase kinematics between delivery methods for the pull shot trials (mean ± SD).

Variable	B	BM (vs. B)	SA_K (vs. B)	SA_U (vs. B)
Stance width (m)	0.544 ± 0.094	0.545 ± 0.076	0.547 ± 0.079	0.547 ± 0.074
COM position (% of base)	56 ± 7	58 ± 5	56 ± 4	56 ± 5
Front shoulder position Y relative to front foot (m)	-0.066 ± 0.067	-0.038 ± 0.055	-0.061 ± 0.053	-0.061 ± 0.062
Front knee position Y relative to front foot (m)	-0.021 ± 0.043	-0.011 ± 0.025	-0.024 ± 0.022	-0.020 ± 0.028
Head position Y relative to front foot (m)	-0.071 ± 0.069	-0.046 ± 0.057	-0.069 ± 0.048	-0.070 ± 0.057
Head position X relative to middle stump (m)	0.096 ± 0.065	0.071 ± 0.078	0.089 ± 0.085	0.092 ± 0.087
Front knee angle X (°)	139 ± 11	139 ± 6	142 ± 7	141 ± 7
Back knee angle X (°)	134 ± 9	141 ± 9*	142 ± 7*	139 ± 18*
Front hip angle X (°)	122 ± 13	125 ± 13	125 ± 12	124 ± 12
Back hip angle X (°)	130 ± 13	133 ± 14	135 ± 13*	133 ± 13*
COM height (m)	0.956 ± 0.055	0.979 ± 0.036	0.982 ± 0.041*	0.973 ± 0.046*
Pelvis angle Z (°)	70 ± 7	71 ± 5	70 ± 5	70 ± 6
Thorax angle X (°)	-41 ± 10	-36 ± 9*	-37 ± 10*	-38 ± 10*
Thorax angle Y (°)	-3 ± 4	2 ± 3*	-1 ± 5*	-2 ± 4*
Thorax angle Z (°)	70 ± 4	70 ± 5	70 ± 4	69 ± 4
Bat angle X (°)	-100 ± 23	-109 ± 24*	-104 ± 22	-104 ± 24
Bat angle Y (°)	-15 ± 10	-19 ± 12	-20 ± 12*	-17 ± 11

Note: B = bowler, BM = bowling machine, SA_K = Sidearm known length, SA_U = Sidearm unknown length, * denotes a significant difference ($p < 0.05$).

Batsmen were found to utilise additional wrist cocking at the top of the backswing (F(2.18, 32.63) = 8.72, $p < 0.01$) when facing the bowling machine compared to the bowlers, with a trend ($p < 0.10$) suggesting a similar pattern when facing the Sidearm in the known length condition. Players also exhibited additional flexion at the front shoulder (F(3, 45) = 6.42, $p < 0.01$) and a lower degree of extension at the back shoulder (F(3, 45) = 5.45, $p < 0.01$) at the top of the backswing when facing the Sidearm in both known and unknown length conditions than when facing the bowlers, as well as a lesser degree of adduction ($F(1.93, 28.92) = 50.29$, $p < 0.001$) and greater external rotation ($F(1.72, 25.74) = 61.84$, $p < 0.001$) of the back shoulder at the top of the backswing when facing the bowling machine compared to the bowlers.

Table 8.13: Differences in kinematics at the top of the backswing between delivery methods for the pull shot trials (mean ± SD).

Variable	B	BM (vs. B)	SA_K (vs. B)	SA_U (vs. B)
Bat angle X (°)	-142 ± 14	-146 ± 13	-147 ± 15*	-146 ± 16
Bat angle Y (°)	-3 ± 11	7 ± 13*	8 ± 15*	4 ± 12*
Max bat angle Y BS (°)	-19 ± 11	-21 ± 13	-23 ± 12*	-20 ± 11
Wrist cocking angle (°)	126 ± 9	122 ± 8*	123 ± 10**	125 ± 10
Bat COM height (m)	1.209 ± 0.122	1.326 ± 0.093*	1.348 ± 0.115*	1.313 ± 0.133*
Top wrist height (m)	0.981 ± 0.092	1.083 ± 0.074*	1.102 ± 0.091*	1.068 ± 0.092*
Bottom wrist height (m)	1.077 ± 0.086	1.150 ± 0.072*	1.171 ± 0.084*	1.142 ± 0.092*
Front elbow angle X (°)	107 ± 12	111 ± 11	110 ± 11	109 ± 13
Back elbow angle X (°)	58 ± 7	58 ± 8	57 ± 8	57 ± 8
Front shoulder angle X (°)	54 ± 10	56 ± 9	60 ± 10*	59 ± 9*
Front shoulder angle Y (°)	-10 ± 13	-13 ± 10	-14 ± 10	-13 ± 11
Front shoulder angle Z (°)	-99 ± 13	-99 ± 12	-99 ± 11	-99 ± 11
Back shoulder angle X (°)	-19 ± 16	-15 ± 11	-10 ± 16*	-10 ± 10*
Back shoulder angle Y (°)	-38 ± 10	-23 ± 8*	-38 ± 9	-38 ± 9
Back shoulder angle Z (°)	-3 ± 15	21 ± 15*	-3 ± 15	-1 ± 13
Pelvis angle X (°)	-21 ± 8	-20 ± 8	-19 ± 8	-19 ± 9
Pelvis angle Z (°)	63 ± 7	61 ± 5	62 ± 6	62 ± 8
Thorax angle X (°)	-39 ± 8	-30 ± 7*	-31 ± 8*	-33 ± 9*
Thorax angle Y (°)	-3 ± 4	2 ± 3	-1 ± 5	-2 ± 4
Thorax angle Z (°)	68 ± 6	69 ± 6	69 ± 6	68 ± 7
X-factor (°)	18 ± 9	10 ± 9*	12 ± 8*	14 ± 9*
Z-factor (°)	6 ± 5	7 ± 4	7 ± 4	6 ± 5

Note: B = bowler, BM = bowling machine, SA_K = Sidearm known length, SA_U = Sidearm unknown length, * denotes a significant difference ($p < 0.05$), ** denotes a significant trend ($p < 0.10$).

Finally, players exhibited a lesser degree of forward flexion of the thorax segment at the top of the backswing ($F(3, 45) = 28.67$, $p < 0.001$), and therefore a smaller X-factor ($F(3, 45) = 33.00$, $p < 0.001$) when facing the bowling machine and the Sidearm in both the known and unknown length conditions than when facing the bowlers.

Assessment of kinematic measures during the weight transfer phase of the pull shot (Table 8.14) showed that batsmen moved their head further backwards in the global anterior-posterior plane ($F(3, 45) = 12.49$, $p < 0.001$) when facing the Sidearm in the known and unknown length conditions than when facing the bowlers. Players were also found to move their whole body centre of mass further backwards in the global anterior-posterior plane ($F(1.60, 23.98) = 10.34$, $p < 0.01$) when facing the Sidearm in the known length condition compared to when facing the bowlers, with a trend ($p < 0.10$) suggesting a similar pattern when facing the Sidearm in the unknown length condition. Lastly, batsmen were found to raise their head significantly less in the global vertical plane during the weight transfer phase ($F(3, 45) = 10.84$, $p < 0.001$) when facing the bowling machine compared to the bowlers.

Table 8.14: Differences in weight transfer phase kinematics between delivery methods for the pull shot trials (mean ± SD).

Variable	B	BM (vs. B)	SA_K (vs. B)	SA_U (vs. B)
COM travel Y (m)	-0.154 ± 0.059	-0.167 ± 0.066	-0.261 ± 0.129*	-0.191 ± 0.069**
COM travel Z (m)	0.161 ± 0.063	0.147 ± 0.056	0.185 ± 0.052	0.180 ± 0.066
Head travel Y (m)	-0.295 ± 0.066	-0.297 ± 0.086	-0.355 ± 0.098*	-0.357 ± 0.095*
Head travel Z (m)	0.201 ± 0.088	0.154 ± 0.080*	0.217 ± 0.078	0.219 ± 0.090

Note: B = bowler, BM = bowling machine, SA_K = Sidearm known length, SA_U = Sidearm unknown length, * denotes a significant difference ($p < 0.05$), ** denotes a significant trend ($p < 0.10$).

Analysis of kinematic measures during the downswing of the pull shot (Table 8.15) showed players to exhibit a smaller maximum X-factor ($F(3, 45) = 31.83$, $p < 0.001$) when facing the bowling machine and Sidearm than when facing the bowlers, as was found at the top of the backswing. Batsmen were found to utilise additional back elbow extension ($F(3, 45) = 12.23$, $p < 0.001$) when facing the Sidearm in both the known and unknown length conditions, and front elbow extension ($F(2.08, 31.12) = 5.47$, $p < 0.01$) when facing the Sidearm in the known length condition, during the downswing compared to when facing the bowlers. Trends ($p < 0.10$) also suggested a similar pattern when facing the bowling machine compared to the bowlers. Finally, players exhibited a significantly lower degree of back shoulder abduction ($F(3, 45) = 8.56$, $p < 0.001$) during the downswing when facing the bowling machine compared to the bowlers.

Table 8.15: Differences in downswing kinematics between delivery methods for the pull shot trials (mean ± SD).

Variable	B	BM (vs. B)	SA_K (vs. B)	SA_U (vs. B)
Max bat speed (°s^{-1})	1798 ± 369	1764 ± 171	1706 ± 211	1726 ± 284
Max bat distal endpoint speed (ms^{-1})	21.07 ± 2.13	21.63 ± 1.16	21.59 ± 1.84	21.81 ± 2.88
Wrist uncocking (°)	54 ± 13	57 ± 10	58 ± 10	58 ± 11
Max X-factor (°)	18 ± 9	10 ± 9*	12 ± 8*	14 ± 9*
Max Z-factor (°)	9 ± 5	10 ± 3	11 ± 3	10 ± 4
Front elbow extension (°)	15 ± 18	27 ± 13**	29 ± 10*	26 ± 17
Back elbow extension (°)	59 ± 16	70 ± 11**	76 ± 8*	72 ± 14*
Front shoulder rotation X (°)	7 ± 17	15 ± 10	13 ± 10	11 ± 12
Front shoulder rotation Y (°)	26 ± 15	18 ± 9	23 ± 9	24 ± 12
Front shoulder rotation Z (°)	3 ± 13	-5 ± 8	-5 ± 8	-3 ± 9
Back shoulder rotation X (°)	64 ± 26	65 ± 18	67 ± 18	65 ± 19
Back shoulder rotation Y (°)	22 ± 12	12 ± 9*	22 ± 9	21 ± 9
Back shoulder rotation Z (°)	58 ± 13	57 ± 11	60 ± 13	59 ± 10

Note: B = bowler, BM = bowling machine, SA_K = Sidearm known length, SA_U = Sidearm unknown length, * denotes a significant difference ($p < 0.05$), ** denotes a significant trend ($p < 0.10$).

Assessment of kinematic measures at the point of impact during the pull shot (Table 8.16) again revealed a number of significant differences between delivery methods. Players were again found to exhibit additional extension at the back knee ($F(1.96, 29.46) = 9.54$, $p < 0.01$) when facing the bowling machine and the Sidearm in the known length condition than when facing the bowlers. A trend ($p < 0.10$) also suggested a more extended back knee against the Sidearm in the unknown length condition than when facing the bowlers. Similarly, the back hip was found to be more extended at the point of impact ($F(1.06, 15.94) = 7.31$, $p < 0.05$) when facing the bowling machine and Sidearm in the unknown length condition than when facing the bowlers. As a result, the whole body centre of mass was again found to be positioned higher in the global vertical axis ($F(3, 45) = 12.59$, $p < 0.001$) at the point of impact when facing the bowling machine and Sidearm in both known and unknown length conditions than against the bowlers. The centre of mass was also found to be positioned further forward relative to the base of support at the point of impact ($F(3, 45) = 7.49$, $p < 0.001$) when facing the bowling machine compared to the bowlers.

Interestingly, the X-factor values were all found to be negative at the point of impact, indicating the thorax was extended backward of the pelvis segment. This separation was found to be significantly greater when facing the bowling machine and Sidearm ($F(3, 45) = 9.38$, $p < 0.001$), indicating that the thorax was angled further backwards of the pelvis when compared to facing the bowlers.

Table 8.16: Differences in kinematics at the point of impact between delivery methods for the pull shot trials (mean ± SD).

Variable	B	BM (vs. B)	SA_K (vs. B)	SA_U (vs. B)
COM height (m)	1.090 ± 0.048	1.119 ± 0.045*	1.137 ± 0.046*	1.123 ± 0.062*
Front knee angle X (°)	160 ± 13	162 ± 11	164 ± 11	162 ± 10
Back knee angle X (°)	137 ± 13	148 ± 12*	148 ± 9*	146 ± 12**
Front hip angle X (°)	143 ± 8	142 ± 8	144 ± 8	143 ± 8
Back hip angle X (°)	176 ± 6	178 ± 7*	165 ± 17	179 ± 7*
Thorax angle X (°)	3 ± 9	3 ± 6	6 ± 7	7 ± 8**
Wrist cocking angle (°)	164 ± 13	163 ± 8	164 ± 8	165 ± 10
X-factor (°)	-3 ± 8	-7 ± 6*	-8 ± 8*	-8 ± 6*
Z-factor (°)	-9 ± 7	-8 ± 6	-9 ± 4	-11 ± 5
Pelvis angle Z (°)	7 ± 15	5 ± 10	7 ± 9	5 ± 9
Thorax angle Z (°)	-2 ± 10	-3 ± 6	-2 ± 7	-5 ± 9
COM position (% of base)	37 ± 9	42 ± 10*	39 ± 9	38 ± 9
Head position Y relative to front foot (m)	-0.316 ± 0.104	-0.290 ± 0.110	-0.331 ± 0.091	-0.347 ± 0.116
Front elbow angle X (°)	123 ± 22	138 ± 16*	139 ± 11*	135 ± 18*
Back elbow angle X (°)	117 ± 14	128 ± 11**	133 ± 10*	129 ± 13*

Note: B = bowler, BM = bowling machine, SA_K = Sidearm known length, SA_U = Sidearm unknown length, * denotes a significant difference ($p < 0.05$), ** denotes a significant trend.

Finally, the front ($F(3, 45) = 7.08$, $p < 0.01$) and back ($F(3, 45) = 11.85$) $p < 0.001$) elbows were both found to be more extended at the point of impact when facing the Sidearm than the bowlers. Similarly, the front elbow was found to be significantly more extended at the point of impact when facing the bowling machine than the bowlers, with a trend ($p < 0.10$) suggesting a similar pattern for the back elbow.

8.4 Discussion

The purpose of this study was to determine differences in delivery characteristics and the resulting kinematic response of a group of elite cricket batsmen when facing a bowling machine and a Sidearm ball thrower compared to when facing a bowler. A number of differences between delivery methods have been identified throughout the analysis. A discussion of the most interesting findings is presented below in two separate sections concerning the forward drives and pull shots respectively.

8.4.1 Forward Drives

Results showed the ball speed from the bowling machine to be significantly faster than those from the bowlers, which were in turn significantly faster than those from the Sidearm in both the known and unknown length conditions. Although the measured ball speed of the bowling machine was significantly higher than the bowlers, there were found to be no significant differences in ball release to impact time. This suggests that either the bowling machine deliveries showed greater deceleration during the flight phase or due to contact with the pitch, or perhaps more plausibly was delivered from slightly further away from the batsman. By delivering the ball from two to three metres closer when using the Sidearm, the coach aimed to replicate the temporal challenge of facing a bowler, however the time between ball release and impact was still significantly longer. This difference in total release to impact time calls into question the validity of the Sidearm in the way it is currently used by coaches as a true representation of batting against a real life fast bowler. Despite this, the similar time between ball bounce and impact across all delivery methods indicates a consistently full length suitable for the forward drive.

When considering the movement timings and durations of batsmen in this study, it is unsurprising that, given the additional time taken for the ball to reach the batsman when facing the Sidearm, in absolute terms the backswing and forward stride began earlier relative to impact in both the known and unknown length conditions. Interestingly the movement initiation time between ball release and the player’s first movement was found to be similar and non-significant across all delivery methods examined. This indicates that the speed of information pickup from any pre-release and early ball flight cues was similar between each delivery method, although it should be noted that all players in this study had considerable experience batting against a bowling machine and a Sidearm, and as such may have developed different and more reliable methods of picking up critical information over time. The increased total movement time and stride duration found when facing the Sidearm suggests a fine attunement to incoming ball speed, perhaps due to experience of previous deliveries, or the time-to-contact variable, indicating that players are aware they have more time to execute the shot and as such take longer in certain phases to ensure an increased likelihood of a successful impact.

Examination of differences in kinematic measures revealed that batsmen position their head, front shoulder, and front knee significantly further forward at the point of release when facing the bowling machine compared to the bowlers. The relatively large variability in head, shoulder, and knee position during the stance phase shows the range of positions adopted by different batsmen relative to the stumps. Batsmen are found to position themselves at different positions on the crease in an attempt to maximize their perceived strengths, and the number of balls they can hit with their preferred batting shots. While there are clearly differences within the group in terms of setup at ball release, the pattern of positioning themselves further forward when facing the bowling machine remains throughout the players tested. Consequently, the whole body centre of mass was positioned significantly further forward of centre relative to the base of support at the time of ball release. This could be attributed to players' increased knowledge of ball bounce position when batting against the bowling machine. The angle of the machine head, along with knowledge of previous deliveries, provides batsmen with pre-release information regarding the approximate trajectory and therefore bounce length of the upcoming delivery. This allows them to begin to organize their movements accordingly earlier in the shot, in this case by positioning their body further forward at the point of ball release in anticipation of playing a forward drive.

Players were also found to adopt a more upright stance, consisting of significantly less forwards flexion in the thorax, a straighter back knee, and a higher centre of mass, when facing the Sidearm compared to the bowlers. This is perhaps a result of the increased time afforded to them to execute the shot when batting against the Sidearm in comparison to the bowlers, with the faster ball speed and shorter reaction times against the bowlers forcing batsmen into a more dynamic position at ball release.

Kinematic measures at the top of the backswing players showed that players exhibited a different backswing technique when facing the bowling machine compared to the bowlers. Batsmen were found to utilise a significantly lower degree of back shoulder extension and adduction during this phase, while also maintaining a straighter backswing about the global anterior-posterior axis. This difference in technique highlights how elite batsmen have begun to develop alternative methods of playing against the bowling machine in order to cope with the different demands placed on them compared to when facing a bowler, and perhaps begins to question the validity of the delivery method in generating a realistic kinematic response. Findings from the Sidearm at the top of the backswing suggest greater similarity in batsman response to when facing the bowler. The only difference of note indicates that the bottom wrist reached a greater height at the top of the backswing when facing the Sidearm in the known length condition than against the bowlers. Although not significantly different, results suggest the bat also reaches a slightly greater angle at the top of the backswing, and as such the bat centre of mass is raised higher when facing the Sidearm compared to the bowlers. This suggests that players make use of the extra time afforded to them by the longer ball release to impact time by raising the bat higher during the backswing phase in order to generate more bat speed in the downswing and correctly time the swing to coincide with the ball's arrival.

During the stride phase batsmen were found to move their head and centre of mass further forwards in the global anterior-posterior, and down in the global vertical planes from their starting positions when facing the Sidearm than the bowlers. The length of the forward stride, and the length of the base created at the end of the stride, was also significantly longer when facing the Sidearm in the known length condition than the bowlers. Although not significant, results suggest a similar pattern with the stride length being slightly longer against the bowling machine than the bowler across the whole group of batsmen. Interestingly, while the stride and total movement of the head and whole body centre of mass were found to be different, the position of the centre of mass as a percentage of the base of support at the end of the forward stride was found to be very similar between all delivery methods. This suggests that players prioritise the transfer of weight into the ball and their position at the completion of the stride over the need for a long forward stride. In the case of the Sidearm trials, where the ball release to impact time is longer, players can afford to utilise a long stride while moving their head and centre of mass further forwards and down to generate the desired weight transfer and position at the end of the stride. When facing the bowling machine batsmen were found to already have their body and centre of mass further forwards at the point of release, so a relatively long stride is still possible alongside less forwards movement of the head and centre of mass in order to achieve the correct position at the completion of the stride. Finally, against the bowlers, batsmen were found to utilise a shorter stride and less forwards movement of the head and centre of mass. However, by shortening the total distance moved, they were still able to achieve the desired weight transfer and position of the centre of mass at the end of the forward stride.

Kinematic measures during the downswing phase showed a trend suggesting batsmen used less front elbow extension when facing the bowling machine than the bowlers, and, although not significant, results suggest a similar pattern when considering extension at the back elbow. This is likely due to a combination of the faster ball speed and players' pre-release knowledge of ball bounce location, whereby batsmen have less time to execute the downswing movement and are in position earlier, but want to ensure the bat is still angled downward at the point of impact to propel the ball along the floor, thus use less elbow extension in their swing. The additional back shoulder flexion found in the Sidearm known length condition is perhaps attributable to the longer stride length exhibited, consequently forcing batsmen to swing their arms and therefore hands further forward into impact.

Finally, at the moment of impact, batsmen were found to display a greater degree of forwards flexion in the thorax segment, and faster forwards motion of the whole body centre of mass when facing the bowling machine and the Sidearm in the known length condition compared to when facing the bowlers. This suggests that, because of the pre-release knowledge of ball bounce length, players are able to organize their forward movement slightly earlier, allowing more time during the ball's flight to flex forwards and transfer their weight into the ball at impact. In the case of the Sidearm in the unknown length condition and the bowlers, batsmen were forced to remain upright for longer in case of a short pitched delivery, thus were unable to generate the same forwards flexion or speed of centre of mass forwards travel at the point of impact.

8.4.2 Pull Shots

As was found in the earlier analysis of the forward drives, ball speed was found to be significantly faster in the bowling machine trials than the bowler trials, which were in turn significantly faster than the Sidearm trials in both the known and unknown length conditions.

The ball release to impact time was again significantly less when facing the bowlers than the Sidearm, although similar when facing the bowling machine compared to the bowlers. This suggests it is likely the bowling machine deliveries were released slightly further away from the batsman or decelerated faster during flight or contact with the pitch, thus took a similar time to arrive at the batsman despite their greater initial speed. Ball bounce was also found to occur earlier relative to impact in the bowling machine and Sidearm trials when compared to the bowlers. While the decreased speed of the Sidearm trials explains the earlier ball bounce event, the fact that the bowling machine deliveries bounced earlier relative to impact than the bowler deliveries suggests that in order to generate a similar amount of vertical bounce the bowling machine deliveries had to bounce earlier in their flight, perhaps due to a slightly lower release height or a lack of backspin compared to the bowler trials.

When assessing the timing of key events and durations of each phase of movement within the pull shot, batsmen were found to begin to move their centre of mass backwards in preparation for the downswing earlier against the Sidearm in the known length condition than the bowlers. A trend also suggested a similar pattern when batting against the Sidearm in the unknown length condition. As in the case of the forward drive, this is attributable to the lower ball speed and therefore longer ball release to impact time experienced when facing the Sidearm compared to the bowlers, and suggests players make use of the extra time available by getting into position earlier to increase the likelihood of a successful shot outcome. Interestingly, and although not significant, results suggested that batsmen also began to move their centre of mass backwards earlier relative to impact when facing the bowling machine than the bowlers. This suggests that, while the ball release to flight times are similar between the two delivery methods, players are able to make a movement decision and begin to organise their movement earlier against the bowling machine, due to the pre-release knowledge of ball bounce location. This was perhaps not found to be significant because of the larger variance found in the timing of the backwards movement of the centre of mass in the bowling machine trials, which was most likely caused by the different technique used by some players in this case, whereby their centre of mass continued to move forwards until later during the downswing, slightly skewing the overall group results.

The movement initiation time was found to be longer when batting against the Sidearm in the known length condition, and although not significant, results suggested a similar trend when facing the bowling machine and the Sidearm in the unknown length condition. In all cases this first movement was the commencement of the backswing. This suggests that when facing the bowlers, players begin to pick up their bat earlier in readiness for an approaching delivery of either a full or short length. Against the Sidearm and the bowling machine however, batsmen are aware either of the length of the approaching delivery, and/or the additional time to play the shot, so can afford to begin their backswing later to maintain a fluid transition from backswing to downswing, and to ensure the correct timing of the downswing to coincide with the arrival of the ball.

During the stance phase of the pull shot, batsmen were found to exhibit a more extended back knee and hip, and consequently a higher centre of mass at the point of ball release against the Sidearm than the bowlers. While the angle of the back hip at ball release was not significantly different between the bowling machine and bowler trials, results indicated the back knee was significantly more extended against the bowling machine, and although not significant, the centre of mass was markedly higher. Players also displayed a lesser degree of trunk forwards and lateral flexion when facing the bowling machine and the Sidearm than the bowlers, a trend which continued through to the top of the backswing. This indicates that, due to the increased ball speed and decreased ball release to impact time against the bowlers, as well as the lack of pre-release knowledge of ball bounce length, batsmen adopted a body position ready for deliveries of either a full or short length released at high speed. When facing the bowling machine and the Sidearm, players either were aware pre-release, or had additional time to assimilate information regarding the ball length and shot decision, thus did not need to adopt such a position. The increased bat angle about the global medio-lateral axis found when facing the bowling machine compared to the bowlers is yet another sign of players' pre-release knowledge of ball bounce location, indicating players were already preparing themselves for a short pitched delivery at the moment of ball release.

At the top of the backswing, batsmen were found to have utilised additional wrist cocking, as well as raised the bat centre of mass, top wrist joint centre, and bottom wrist joint centre higher in the global vertical plane when facing the bowling machine and the Sidearm than the bowlers. The bat was also found to exhibit an angle towards the leg-side in the global anterior-posterior plane at the top of the backswing in all these cases, as opposed to against the bowler in which case the bat was angled slightly towards the off-side. This is again indicative of earlier pickup of ball length and therefore shot decision information when facing the bowling machine and the Sidearm, either due to the pre-release knowledge of ball bounce location or a slower ball speed, allowing players additional time to raise the bat in preparation for the pull shot.

Analysis of shoulder joint kinematics revealed a fundamentally different backswing technique when facing each of the different delivery methods. Batsmen were found to exhibit additional front shoulder flexion and a lesser degree of back shoulder extension when facing the Sidearm compared to the bowlers, while displaying less back shoulder adduction and greater external rotation when facing the bowling machine. While the reasons behind the development of these techniques are hard to extract, it is clear that the elite players in this study have adopted varying kinematic responses to each of the delivery methods used, most likely in order to increase the likelihood of shot success. This suggests that through practice elite players are perhaps attuned to a different set of specifying variables when facing the bowling machine and the Sidearm compared to the bowler, finding more efficient methods to combat the challenges of each delivery method through their batting technique. These findings strongly call into question the validity of each delivery method, in their current state, as a truly realistic representation of facing a real life bowler, and as such highlight the value of batting against a bowler in practice as frequently as possible. Players who rely too heavily on the bowling machine or the Sidearm in practice, may develop techniques, movement patterns, and attunement to cues that are in fact non-optimal when facing a bowler in a match situation, and as a result limit their skill or rate of improvement.

In the weight transfer phase batsmen were found to move their head and centre of mass further backwards in the global anterior-posterior plane when facing the Sidearm compared to the bowlers. As in the forward drives, the extra time afforded to the players by the lower ball speed and longer ball release to impact time allows them additional time to move back into position. Players were found to use this time to move further back, giving them extra time to view the ball's trajectory and get into a better position to ensure a successful impact.

Assessment of kinematic measures during the downswing phase found players to exhibit a greater degree of front and back elbow extension when facing the Sidearm and the bowling machine compared to the bowlers. As a consequence, both elbows were also found to be more extended at the point of impact against the Sidearm and the bowling machine. This displays a greater level of readiness for the pull shot in these cases, as opposed to when facing the bowlers where players had to be ready for both full and short deliveries released at pace, thus did not have the time to achieve so much elbow extension during their downswing. Similarly, batsmen were found to achieve a smaller maximum X-factor when facing the bowling machine and the Sidearm. This pattern remained at the point of impact where, although the thorax was extended slightly backwards of vertical in all cases, it remained further forward when facing the bowler compared to the Sidearm and bowling machine. This shows the players' eagerness to flex their thorax forward when facing the bowler in preparation for a potentially full pitched delivery, whereas the pre-release knowledge of ball bounce location and additional time between ball release and impact allows them to sit back more against the bowling machine and Sidearm delivery methods. Players are unlikely to have the time to achieve the same degree of thorax extension at the point of impact when facing the bowler, due to the additional flexion found during at the top of the backswing and during the downswing phase.

At the moment of impact, as was found at the moment at release, players exhibited a higher centre of mass, and greater extension of the back knee and hip when facing the bowling machine and Sidearm than the bowlers. The centre of mass was also found to be significantly further forward relative to the base of support when facing the bowling machine compared to the bowlers. This is again indicative of a pre-release knowledge of ball bounce location, with players being able to adopt a more upright body position from which to hit down and over the top of the ball.

8.5 Conclusions and Application to Coaching Practice

This study has identified a range of differences in delivery characteristics, movement timings and durations, and kinematic response of elite batsmen when facing three different delivery methods in comparison to real life bowlers. The results indicate that batsmen utilise fundamentally different techniques in each case, and call into question the validity of both the bowling machine and the Sidearm, in the way they are currently used, as providing an accurate and realistic representation of batting against a bowler. Although this study possesses some limitations, particularly in terms of the low number of trials completed by some subjects against the Sidearm and bowler, the large number of statistical differences found between delivery methods gives confidence that the findings are real and the data has not been skewed.

While the bowling machine trials were similar to the bowlers in terms of ball speed and release to impact time, a number of differences were found in movement timings and kinematic response. It is suggested that the majority of differences found between the Sidearm trials, particularly in the unknown length condition, and the bowler trials were as a result of the significantly lower ball speed and longer release to impact time. Therefore, it is recommended that coaches and players are wary of over-using the bowling machine in training, as it is likely to create different movement patterns and attune players to different cues compared to facing a bowler. While the bowling machine may be useful to avoid injuries to bowlers through increased workload, and to create control and repeatability in order for a batsman to practice generating more stable movement patterns for a given shot, they should not act as a replacement for training against bowlers. This ability for coaches to create control and repeatability with the bowling machine is perhaps most useful in the early stages of a player's development, where the development of stable movement patterns is important, and simply hitting a large volume of balls is likely to cause substantial improvement, or in trying to learn a particular shot for which ball delivery requires high levels of accuracy. Although the results of this study indicate that perhaps the Sidearm is a more realistic and appropriate substitute for batting against a bowler, coaches must make an effort to ensure the temporal demands of the deliveries are realistic to what the batsman will face in a match situation.

Future studies should investigate the skills and techniques of batsmen whose training is conducted largely using a bowling machine, in comparison to those using primarily the Sidearm and bowlers, in an attempt to discover the effects each has on a player's development and learning of movement patterns. Researchers should also look to conduct studies with larger subject groups and more complete trials in each category, in order to further increase confidence in the findings presented.

CHAPTER 9

RELATIONSHIPS BETWEEN BATTING TECHNIQUE AND BALL CARRY DISTANCE IN A RANGE HITTING TASK

9.1 Introduction

The ability of a batsman to consistently hit the ball hard and clear the boundary has become a major contributor to batting success in the modern game. With the advent of T20 cricket, and the increasing scores and strike rates found in one-day and test matches, range hitting has become a critical skill and a frequent addition to training. The best hitters regularly clear boundaries over 80 m, with some shots being measured to carry in excess of 100 m. An understanding of the mechanics of how batsmen generate carry distance, in addition to a comprehension of those aspects of technique which best predict large carry distances, would be extremely beneficial to the coaching of range hitting.

To date there have been no studies into range hitting in cricket, and as such the key parameters and techniques used by batsmen are not fully understood. While existing cricket batting studies have investigated the speed of the bat during the downswing of the forward drive (e.g. 21.2 ms^{-1}; Stuelcken et al., 2005), and the presence of kinetic chaining in the forward drive (Stretch et al., 1998; Elliott et al., 1993; Stuelcken et al., 2005), no consensus has been formed on typical bat speeds or how that speed is generated (section 2.8.1). Despite this lack of research in cricket, several studies have investigated bat/clubhead speed generation in golf and baseball (section 2.9), identifying the separation between the pelvis and thorax segments in the transverse plane (referred to as the X-factor in golf; Cheetham et al., 2001; Myers et al., 2008; Chu et al., 2010), weight transfer (Wallace et al., 1990; Koenig et al., 1994; Chu et al., 2010) and front knee extension (Welch et al., 1995) in the approach to impact, trunk flexion and lateral bending (Chu et al., 2010), and wrist uncocking (Robinson, 1994) as key determinants of clubhead and ball speed, and carry distance. The aim of this study was therefore to identify the key parameters and techniques characterising those batsmen able to generate large carry distances, ball launch speeds, and bat speeds when range hitting, and the mechanics behind this ability.

9.2 Methodology

9.2.1 Subjects

Twenty cricket batsmen (mean ± SD: age = 22.5 ± 3.1 years; height = 1.82 ± 0.04 m; mass = 80.0 ± 7.8 kg) participated in this investigation. Subjects included one batsman with full international playing honours, two from the England Lions squad, three county players, six that had represented England under 19's, five premiership club batsmen, and three lower standard club batsmen. In this case the mix of batsman abilities in the study was seen as an advantage, as a range of techniques, ball speeds, and bat speeds were generated, providing additional data to extract trends and relationships between variables.

9.2.2 Data Collection and Processing

Each batsman hit a series of forward drives (mean ± SD = 14.0 ± 3.6 trials per subject) against the bowling machine, aiming to hit the ball straight back over the bowler's head for six, as described in section 3.9.2. Batsmen were encouraged at each stage to perform their shots as they would in a match environment, while aiming for maximum carry distance in each shot. Balls were projected into a suitable area for the shot as directed by the batsman, with inbound speed on the approach to impact, calculated using differentiated ball position data over a 40 ms interval, of 25.0 ± 1.3 ms^{-1}. Each batting shot was captured by an 18 camera Vicon motion analysis system and three high-speed video cameras, all operating at 250 Hz as outlined in section 3.7. Sixty-two retro reflective markers were positioned on the body, bat, ball, and stumps (section 3.6). Trials were then reconstructed, manually labelled and filtered (section 4.3), before a biomechanical model was applied (section 4.4) and a series of key events automatically identified for each shot type (section 4.5.2).

9.2.3 Data Reduction

9.2.3.1 Stage 1 – Carry Distance

Initially only trials where the ball was projected forwards in the anterior-posterior plane post-impact (horizontal launch angle; Figure 9.1) were selected for analysis (n = 239; mean = 12.0 ± 2.4 trials per subject). Subsequent analyses required a further reduction in the number of trials selected; this was achieved by narrowing the selection criteria in terms of the post-impact vertical ball launch angle (Figure 9.2). The three resulting data sets are listed below:

- All trials - horizontal launch angle -90° to 90° (n = 239)
- Vertical launch angle 10° to 70° (n = 200)
- Vertical launch angle 20° to 60° (n = 140)

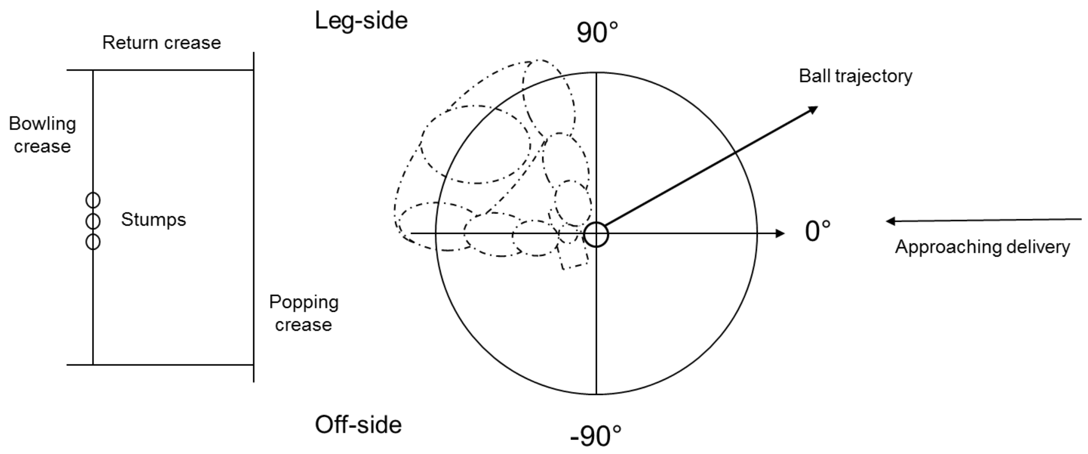


Figure 9.1: Horizontal ball launch angle.

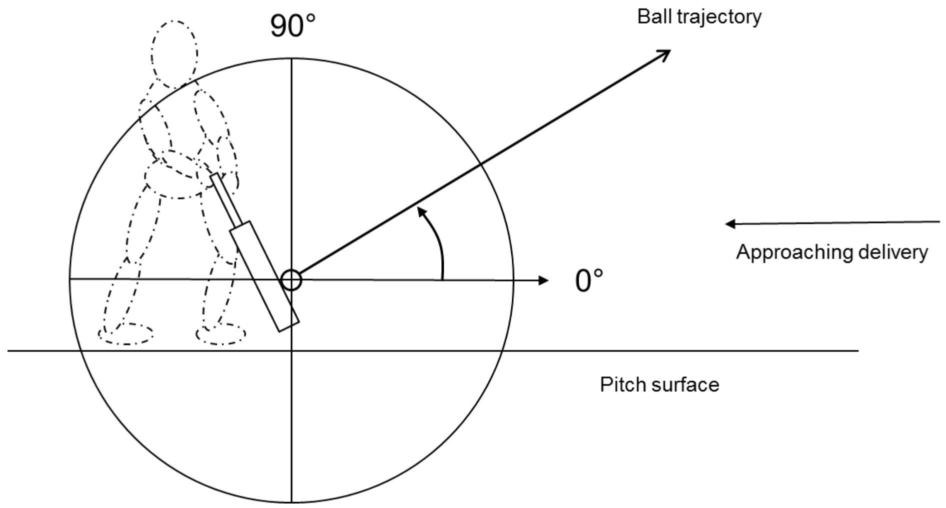


Figure 9.2: Vertical ball launch angle.

The ball carry distance, vertical launch angle, and launch speed (from the ball flight model; section 4.5.3) were extracted from each trial and used for later analyses. A 'centred launch angle squared' variable was also determined from the launch angle measure of each trial to allow for a non-linear (quadratic) component to be added to the model predicting carry distance, as the relationship between launch angle and ball carry distance was found to be quadratic in nature. This was calculated as the measured launch angle for a given trial minus the mean launch angle, squared. Not only does this help avoid collinearity problems in the regression model between the two launch angle components, but also doesn't change the R^2 values of the model, just the regression parameters.

9.2.3.2 Stage 2 – Ball Launch Speed

As in the previous stage, initially only trials where the ball was projected forwards in the anterior-posterior plane post-impact were selected for analysis (n = 239; mean = 12.0 ± 2.4 trials per subject). Further data reduction for subsequent analyses was conducted via the narrowing of selection criteria in terms of post-impact vertical (Figure 9.2) and horizontal launch angles (Figure 9.1). The resulting data sets are listed below:

- All trials - horizontal launch angle -90° to 90° (n = 239)
- Horizontal launch angle -45° to 45° (n = 219)
- Horizontal launch angle -30° to 30° (n = 189)
- Horizontal launch angle -15° to 15° (n = 132)
- Vertical launch angle 10° to 70° (n = 200)
- Vertical launch angle 20° to 60° (n = 140)
- Vertical launch angle 20° to 60° and horizontal launch angle -45° to 45° (n = 138)
- Vertical launch angle 20° to 60° and horizontal launch angle -30° to 30° (n = 113)
- Vertical launch angle 20° to 60° and horizontal launch angle -15° to 15° (n = 73)

The ball launch speed (from the ball flight model; section 4.5.3), impact location relative to the sweetspot in the medio-lateral (X) and vertical (Z) planes of the bat (as determined using the impact location methodology in chapter 6), maximum pre-impact resultant bat distal endpoint speed, and bat mass were extracted from each trial and used for later analyses.

9.2.3.3 Stage 3 – Bat Speed

The best three trials in terms of maximum pre-impact resultant bat distal endpoint speed and ball launch speed were identified for each subject. While not all selected trials in terms of maximum pre-impact resultant bat distal endpoint speed were associated with a subjectively successful impact and may have been edged or mishit, selected trials in terms of maximum ball launch speed were found to be associated with an impact location near the sweetspot and as a result a more successful impact, hence their inclusion in this stage of the analysis. A series of 70 kinematic parameters (a subset of those presented and defined in section 4.5.3) were then extracted from the biomechanical model for each trial in four distinct groups; kinematics at the top of the backswing, maximum and minimum kinematic features during the downswing, downswing range of motion, and kinematics at impact. These parameters were:

Kinematics at the top of the backswing:

- Bat angle (X, Y, Z)
- Wrist cocking angle
- Bat COM height
- Wrist JC height (top and bottom)
- Elbow angle X (front and back)
- Front shoulder angle (X, Y, Z)
- Back shoulder angle (X, Y, Z)
- Pelvis angle (X, Y, Z)
- Thorax angle (X, Y, Z)
- X-factor
- Z-factor

Maximum and minimum kinematics in the downswing:

- Maximum X-factor
- Maximum Z-factor
- Minimum wrist cocking angle

Downswing range of motion:

- Pelvis rotation (X, Y, Z)
- Thorax rotation (X, Y, Z)
- X-factor uncoiling (max – impact)
- Z-factor uncoiling (max – impact)
- COM travel stride start to impact (Y, Z)
- COM total travel Y
- Wrist uncocking
- Elbow extension (front and back)
- Front shoulder rotation (X, Y, Z)
- Back shoulder rotation (X, Y, Z)
- Downswing duration
- Bat angular rotation

Kinematics at impact:

- Bat angle X
- Wrist cocking angle
- Elbow angle X (front and back)
- Front shoulder angle (X, Y, Z)
- Back shoulder angle (X, Y, Z)
- Pelvis angle (X, Y, Z)
- Thorax angle (X, Y, Z)
- X-factor
- Z-factor
- Base length
- COM speed Y
- Bat COM position Y relative to front knee
- Bat COM position Y relative to head

9.2.4 Statistical Analysis

All statistical analysis was performed within SPSS v.22 (SPSS Corporation, USA). Forward stepwise multiple linear regressions were conducted in stages one and two of the analysis to explain the variance in ball carry distance and ball launch speed respectively. The requirement for the inclusion of a variable was set at $p < 0.05$, with the removal level set at $p > 0.05$ throughout.

In stage three, the variation observed in each technique parameter was assessed using an analysis of variance. The between-batsman variability (standard deviation of the observations) was compared with the mean standard deviation of the between-trial variability for each subject. This averaged 37.4% and 36.5% for the highest bat speed and ball launch speed trials respectively when considering only the parameters calculated in this study. Interestingly increased variation was found in the downswing and impact sections of the analysis, accounting for a marked increase in the total percentage variation. As there was generally good between-trial repeatability for the majority of kinematic parameters, the three trials selected in each case were averaged to provide representative data for each batsman.

Further forward stepwise multiple linear regressions were then carried out to examine the effect of interactions between kinematic variables on maximum pre-impact resultant bat distal endpoint speed when considering both the best individual trials and the average of the three best trials in terms of bat speed and ball launch speed. A maximum of four variables were included in the predictive equations at this stage, again with the requirement for the inclusion of a variable being $p < 0.05$, and a subsequent removal level of $p > 0.05$.

9.3 Results

9.3.1 Stage 1 – Carry Distance

The 239 trials initially selected for this analysis displayed resultant carry distances (calculated by the flight mode; section 4.5.3) of 11.4 – 106.2 m (mean ± SD = 53.7 ± 19.7 m). Details of the range, mean, and standard deviation measures of each calculated launch parameter used throughout this stage are shown in Table 9.1.

Table 9.1: Details of the range, mean, and standard deviation of each launch parameter calculated for the range hitting trials.

Variable	Range	Mean ± SD
Vertical ball launch angle (°)	1.1 – 89.5	35.5 ± 20.4
Horizontal ball launch angle (°)	-88.7 – 87.1	-4.2 ± 25.9
Ball launch speed (ms^{-1})	18.13 – 39.59	28.62 ± 4.24
Impact location X (m)	-0.068 – 0.081	0.017 ± 0.033
Impact location Y (m)	-0.201 – 0.221	0.021 ± 0.067
Max. bat distal endpoint speed (ms^{-1})	17.21 – 30.93	25.67 ± 1.96

The best individual predictors of ball carry distance were the centred launch angle squared and launch angle variables, between them explaining 60.5% of the variance (Table 9.2). Larger carry distances were associated with a launch angle nearer to the optimum launch angle (as calculated from the ball flight model; section 4.5.3) of 42°. The highest percentage variance in ball carry distance was explained using all three parameters; centred launch angle squared, launch angle, and launch speed. This combination of variables explained 92.1% of the variance, with an additional 31.6% being explained through the addition of ball launch speed (Table 9.2). The trials with the largest carry distance were not only launched near to the optimum launch angle, but also with the highest speed.

Table 9.2: Details of the predictive equations produced using linear regression to explain the variance in ball carry distance.

Model	Variable	Unstandardized B Coefficient	p-value	Percentage Explained
1	Centred launch angle^2	-0.022	< 0.001	32.7
2	Centred launch angle^2	-0.029	< 0.001	60.5
	Launch angle	0.540	< 0.001	
3	Centred launch angle^2	-0.025	< 0.001	92.1
	Launch angle	0.672	< 0.001	
	Launch speed	2.774	< 0.001	
	Constant	-39.360	< 0.001	

By narrowing the selection criteria in terms of the required launch angle to be taken forward for subsequent analysis (as discussed in section 9.2.3.1), a higher percentage of variance was explained by the three variables included in the regression model. By selecting only the trials with a vertical ball launch angle between 10° and 70°, 97.4% of the variance in carry distance was explained, and when assessing just the trials with a vertical ball launch angle between 20° and 60°, 99.2% of the variance in carry distance was explained. By this final stage, the importance of ball launch angle and centred launch angle squared had dropped substantially to a combined explained variance of 10.2%, while the importance of ball launch speed had increased considerably to 89.0%.

9.3.2 Stage 2 – Ball Launch Speed

Details of the range, mean, and standard deviation measures of each calculated launch parameter used throughout this stage are shown in Table 9.1. The best individual predictor of ball launch speed was the distance of ball impact from the sweetspot of the bat in its medio-lateral plane (impact location X), explaining 27.8% of the variance in ball launch speed. Through the addition of the bat speed and impact location Y variables, the total explained variance in ball launch speed had increased to 70.0% (Table 9.3), with bat speed and impact location Y adding a further 25.3% and 16.9% variance explained respectively. This indicates that trials with an impact location nearer the sweetspot of the bat in both the medio-lateral and vertical plane of the bat, and with a higher bat speed at the time of impact, will produce a higher ball launch speed.

Table 9.3: Details of the predictive equations produced using linear regression to explain the variance in ball launch speed.

Model	Variable	Unstandardized B Coefficient	p-value	Percentage Explained
1	Impact location X	-105.429	< 0.001	27.8
2	Impact location X	-112.840	< 0.001	53.1
2	Bat speed	1.072	< 0.001	
3	Impact location X	-108.670	< 0.001	70.0
3	Bat speed	0.983	< 0.001	
3	Impact location Y	-40.009	< 0.001	
3	Constant	8.435	< 0.001	

Further narrowing of the selection criteria in order for a trial to be taken forward into analysis (as discussed in section 9.2.3.2) found some changes in total explained variance and the relative importance of each parameter included in the regression model. Basic details of the final predictive model for each separate regression analysis performed are shown in Table 9.4). While adjustment of the entry criteria according to horizontal launch angle alone made little difference to either the total explained variance or relative importance of each parameter, narrower criteria according to vertical launch angle found a slight increase in total explained variance (74.6% for model five). A further increase in total explained variance was found in models six to eight (reaching a peak of 78.0%), as well as a relative increase in the importance of bat speed in the regression model, with its individual contribution reaching 39.1% of the total explained variance in model eight.

Table 9.4: Basic details of the separate linear regression models produced to explain the variance in ball launch speed under narrower selection criteria.

Model	Horizontal launch angle (°)	Vertical launch angle (°)	Variable	Cumulative Percentage Explained
1	-45 to 45	0 to 90	Impact location X	26.7
			Bat speed	50.8
			Impact location Y	**68.3**
2	-30 to 30	0 to 90	Impact location X	23.2
			Bat speed	48.9
			Impact location Y	**67.3**
3	-15 to 15	0 to 90	Impact location X	20.5
			Bat speed	53.8
			Impact location Y	**71.6**
4	-90 to 90	10 to 70	Impact location X	27.1
			Bat speed	51.0
			Impact location Y	**70.4**
5	-90 to 90	20 to 60	Impact location X	25.9
			Bat speed	48.8
			Impact location Y	**74.6**
6	-45 to 45	20 to 60	Impact location X	25.6
			Bat speed	52.0
			Impact location Y	**74.8**
7	-30 to 30	20 to 60	Impact location X	21.5
			Bat speed	49.8
			Impact location Y	**72.8**
8	-15 to 15	20 to 60	Impact location X	19.6
			Bat speed	58.7
			Impact location Y	**78.0**

9.3.3 Stage 3 – Bat Speed

9.3.3.1 Highest Bat Speed Trials

Assessment of the three averaged trials with the highest pre-impact resultant bat distal endpoint speed for each subject revealed that the best individual kinematic predictor of bat speed was the distance in the global anterior-posterior plane from the front knee joint centre to the centre of mass of the bat at the time of impact (bat COM Y relative to front knee), explaining 57.7% of the variance in bat speed. This indicates that trials where the ball is impacted further ahead of the front knee are associated with a higher bat speed immediately prior to impact. Three additional variables; the angle of the pelvis about the global vertical axis at the top of the backswing (pelvis angle Z top BS; 14.0%), the angle of the bat about the global vertical axis at the top of the backswing (bat angle Z top BS; 11.1%), and the total distance travelled by the whole body centre of mass in the global anterior-posterior plane (COM total travel Y; 4.3%), were also included in the final model (Table 9.5) and together increased the total variance explained to 87.0%. The batsmen who generated the highest bat speed displayed a more side-on pelvis at the top of the backswing, a lower bat angle about its longitudinal axis at the top of the backswing, and a larger total forward travel of the whole body centre of mass in the global anterior-posterior plane during the shot.

Table 9.5: Details of the final predictive equation produced using linear regression to explain the variance in bat speed for trials with the highest pre-impact resultant bat distal endpoint speed.

Technique Parameter	Unstandardized B Coefficient	p-value	Percentage Explained
Bat COM Y relative to F knee impact	5.936	< 0.001	
Pelvis angle Z top BS	0.072	< 0.01	
Bat angle Z top BS	-0.038	< 0.01	87.0
COM total travel Y	3.359	< 0.05	
Constant	27.505	< 0.001	

9.3.3.2 Highest Ball Launch Speed Trials

The best individual kinematic predictor of bat speed when considering the three averaged trials with the highest ball launch speed for each subject was the maximum angular separation in the downswing between the pelvis and thorax segments in the transverse plane (max Z-factor), explaining 41.6% of the variance in bat speed. A further 29.8% of the variance in bat speed was explained by the addition of the magnitude of front elbow extension (F elbow extension DS) and wrist uncocking (wrist uncocking DS) present during the downswing, accounting for 15.1% and 14.7% of the variance respectively, and increasing the total variance explained to 71.4% (Table 9.6). This model shows that trials where subjects display a larger maximum angular separation between the pelvis and thorax segments, and a greater magnitude of front elbow extension and wrist uncocking during the downswing, are indicative of a higher maximum bat speed.

Table 9.6: Details of the predictive equations produced using linear regression to explain the variance in bat speed for trials with the highest ball launch speed.

Model	Technique Parameter	Unstandardized B Coefficient	p-value	Percentage Explained
1	Max Z-factor	0.156	< 0.01	41.6
2	Max Z-factor	0.148	< 0.01	56.7
	F elbow extension	0.054	< 0.05	
3	Max Z-factor	0.134	< 0.01	71.4
	F elbow extension DS	0.062	< 0.01	
	Wrist uncocking DS	0.069	< 0.05	
	Constant	17.622	< 0.001	

9.4 Discussion

The best individual predictor of total carry distance was the proximity of the ball's vertical launch angle to the optimal angle of 42°, closely followed by the ball launch speed. As expected, the shots that carried the furthest were launched at a high speed and at a vertical launch angle close to 42° above the horizontal. The fact that the launch angle variable was found to be a more important predictor of carry distance than ball launch speed when considering the full set of successful trials highlights that it is impossible to generate large carry distances with a very low or very high launch angle, irrelevant of how fast the ball is launched. However, as the launch angle approached a more optimal range, as in the subsequent sets of trials (vertical launch angles from 10° to 70° and 20° to 60° respectively), the importance of ball launch speed to predicting total carry distance increased dramatically. This finding suggests that when learning to hit over the top, players should initially focus on getting the launch angle correct, before attempting to increase ball launch speed. This approach allows a greater margin for error in generating a large carry distance, as a small change in ball launch speed has a smaller effect on carry distance than a change in launch angle. Once a player possesses the technique and timing to consistently launch the ball at the correct angle, increasing ball launch speed becomes of additional importance.

The observed increase in total explained variance found when narrowing the selection criteria for the inclusion of a trial according to vertical launch angle suggests that some errors are present in the ball tracking or flight model at extremely low or high ball angles, with increased or decreased spin on the ball potentially having a greater effect on carry distance than in other trials. However, the 92.1% to 99.2% of variance in carry distance explained by the three predictive equations indicate that the key parameters in generating large carry distances have been established.

In the original predictive equation explaining the greatest percentage of variation observed in ball launch speed, the most important predictor was found to be the distance of impact from the midline of the bat in the medio-lateral plane. This indicates that impacts nearer the midline of the bat generated a higher ball launch speed, and is in agreement with the findings regarding the effects of impact location in chapter 6. Similarly, the proximity of impact to the sweetspot in the vertical plane of the bat was found to have a significant effect on ball launch speed, with impacts nearer the sweetspot producing faster ball launch speeds. This result also shows that an increased bat speed in the approach to impact enables batsmen to launch the ball at higher speeds, with bat speed accounting for 25.3% of the variance in ball launch speed. The combined importance of impact location, together explaining 44.7% of the variance 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 a higher bat speed but without the required accuracy.

Narrowing of the selection criteria for the inclusion of a trial according to horizontal and vertical launch angles found a relative increase in the importance of bat speed to ball launch speed, as well as an overall increase in the total variance explained. This suggests that trials with near-optimal launch parameters in terms of vertical and horizontal angles are likely to be associated with a more optimal impact location, thus increasing the contribution of bat speed to explaining the variance between these trials. This also demonstrates that for players who are able to consistently generate near-optimal impact locations and initial launch angles, the pre-impact bat speed is likely to play a big part in differentiating between trials in terms of total carry distance, and is worth increasing via technical and physical training.

When assessing the variance in bat speed using the trials with the highest measured peak bat speed, the most important predictor was found to be the distance of the bat in front of the front knee in the global anterior-posterior plane at the point of impact, alone explaining 57.7% of the variance. This indicates that trials where the impact point occurred further ahead of the front knee produced a faster peak bat speed. This is likely as a result of the batsman having a larger distance and period of time during the downswing to accelerate the bat towards impact. This predictive equation also suggested that the pelvis angle at the top of the backswing in the transverse plane, the bat angle about the global vertical axis at the top of the backswing, and the total forward travel of the whole body centre of mass in the global anterior-posterior plane, all played a significant role in explaining the variance in bat speed, although to a much smaller extent.

Although the total explained variance in bat speed was found to be high in this case, not all trials where the bat speed was highest generated a good impact location or resulting shot outcome. As such it was decided to investigate those trials with the highest ball launch speed, in an attempt to explain the variance in bat speed across those trials. The best individual predictor of bat speed in this case was found to be the maximum Z-factor achieved during the downswing; a measure of the separation in the downswing between the pelvis and thorax segments in the transverse plane. This is in line with findings in golf (Cheetham et al., 2001; Myers et al., 2008; Chu et al., 2010) where the 'X-factor' has been found on numerous occasions to be important in generating clubhead speed during the downswing. The trials where batsmen exhibited a greater maximum separation between the pelvis and thorax segment during the downswing were indicative of a higher maximum bat speed.

The degree of front elbow extension and wrist uncocking during the downswing were also significant contributors to bat speed, with additional elbow extension and wrist uncocking being found to increase peak bat speed during the downswing. Again this is in line with research in golf and baseball, where the cocking and uncocking of the wrists has been found to significantly increase clubhead and bat speed (Robinson, 1994; Welch et al., 1995; Chu et al., 2010). There is likely to be an optimal amount of elbow extension and wrist uncocking during the downswing, beyond which bat speed decreases and the accuracy of impact is reduced, as batsmen are unable to coordinate the technique required to control larger degrees of motion.

While the relatively small sample size presented a problem with regression analysis and the number of technique parameters which could be identified as explaining the variance in bat speed, the total variance explained of 87.0% and 71.4% in the predictive equations suggest that the key aspects of technique have been identified.

9.5 Conclusions and Application to Coaching

This study has identified a series of parameters which explain the majority of the variance in ball carry distance when range hitting in cricket. The results indicate that a launch angle close to 42° and a high launch speed are critical to generating a large carry distance, and that an impact location near the sweetspot of the bat in both the medio-lateral and vertical planes, along with a high bat speed are important in achieving a high ball launch speed. Analysis of technique variables has revealed four characteristics which in combination explain a large percentage of the variance in bat speed. The predictive equations suggest that the trials with the highest bat speed exhibited an impact location further ahead of the front knee in the global anterior-posterior plan, implying a longer downswing allows additional time and space to accelerate the bat into impact. The biggest hitters also exhibited a greater maximum Z-factor (the separation between the pelvis and thorax segments in the transverse plane), and additional front elbow extension and wrist uncocking during the downswing.

The results of this investigation have the potential to be very useful in the coaching of range hitting to both elite and developing batsmen. It is suggested that batsmen should initially focus on the ability to generate a consistently good impact location and launch angle before progressing onto developing additional bat speed through technical changes. However, with the elite population studied here, technical changes to increase bat speed could provide significant improvement in hitting ability. Future studies should investigate further the use of a kinetic chain during a range hitting task in cricket, in particular examining the timing of peak rotational and segmental velocities during the uncoiling/downswing phase. Researchers should also look to investigate additional batting shots, for example hitting over the leg side, and seek to determine the kinematic factors important for consistently generating an impact location near the sweetspot of the bat and a consistently near-optimal launch angle. Finally, studies examining the effects of delivery type (speed, line, and length) on a player's ability to consistently hit over the top, and the technical changes required to achieve success under different conditions, could have potentially substantial benefits to players and coaches.

CHAPTER 10

SUMMARY AND CONCLUSIONS

10.1 Chapter Outline

The purpose of this study was to develop a methodology by which the three-dimensional kinematics of cricket batting could be analysed in a realistic training environment, and utilise this methodology to investigate a series of research questions regarding batting technique and coaching practice. Within this chapter, the extent to which these aims have been achieved through the development and application of a biomechanical model and the analysis of its outputs, is assessed. The research questions posed in chapter 1 are addressed, as well as the limitations of this work, and potential future studies are proposed.

10.2 Thesis Summary

10.2.1 Data Collection

Data were collected for a group of thirty-one cricket batsmen (23 from the ECB elite and development squads, 8 club batsmen; section 3.8) in an indoor cricket practice facility. Batsmen performed a series of forward drives and pull shots in a range of different situations and against a range of delivery methods (section 3.9), including hitting a static ball off a batting tee, and against a bowling machine, Sidearm ball thrower, and bowler. Some batsmen also completed a range hitting drill against the bowling machine. While not all batsmen completed the full testing protocol, sufficient data was captured to address each of the topic areas intended.

A novel marker set to incorporate markers on the pads and helmet of the batsman was developed (sections 3.4, 3.5, and 3.6), and a Vicon Motion Analysis System used to collect full body three-dimensional kinematic data (250 Hz) for each trial. Markers were also positioned on the bat and ball in order to track their positions in three-dimensional space. Synchronous high-speed video (250 Hz) captured aspects of ball flight that occurred outside of the Vicon capture volume (section 3.7). Various mass and size characteristics of each subject’s bat were also recorded (section 3.10).

10.2.2 Data Processing

Trials suitable for further analysis, determined via the type and success of the shot played (according to the scale proposed by Weissensteiner et al., 2009), were identified for each batsman for inclusion in the study. Trials were then reconstructed and labelled (sections 4.3.1 and 4.3.2), and any gaps in the tracked marker positions filled using one of a selection of methods, depending on the specific situation (section 4.3.3). A Butterworth filter with a low-pass cutoff frequency of 15 Hz was also used to remove some of the inevitable noise generated when using a marker based motion tracking system.

A full body kinematic model of the batsman was then developed and applied to each batting trials (section 4.4). The human body was represented as a system of 13 rigid segments, including the head and neck; thorax; pelvis; 2x upper arms; 2x forearms; 2x thighs; 2x shanks; and 2x foot segments, along with a bat, ball, and set of stumps (section 4.4.1). A three-dimensional local coordinate system was defined for each segment, allowing segmental orientations and joint angles to be calculated (section 4.4.2). A series of key events throughout each shot were then defined (section 4.5.2), and descriptions of important variables in terms of delivery characteristics, shot outcome, movement timings, and kinematics, from the model were provided (section 4.5.3).

10.2.3 Data Analysis

Having defined the biomechanical model of the batsman, bat, and ball, its outputs were used in a number of different analyses. Initially, data from the bowling machine trials was summarized into a biomechanical description of the forward drive and pull shots for the batsmen in this study. This provided a platform for a number of questions from previous research and as a result of the thorough biomechanical description to be addressed using simple statistical analyses. Next, bat and ball marker trajectories were used to develop a methodology for determining the impact location of the ball on the bat face, and its effect on the resulting shot outcome in terms of ball speed, bat twist, and ball direction

Having presented a thorough biomechanical description of each shot, data from the biomechanical model was finally used to address the remaining three research questions posed using separate analyses. Firstly, the presence of movement variability in batting, and the effect of skill level and delivery method, was investigated, followed by a detailed analysis of the effects of facing different delivery methods on batsman response in both the forward drive and pull shots. Finally, the relationships between batting technique and ball carry distance in a range hitting task were assessed using a regression analysis. Summaries of the results of each of these studies are presented below.

10.3 Research Questions

Q1. What are the techniques and movement timings employed by batsmen in the forward drive and pull shots?

The movement timings and kinematics exhibited by batsmen in this study during the forward drive and pull shots have been presented in detail. Strong couplings were found in the forward drive between the commencement of the backswing and forward stride events, and the completion of the forward drive and ball bounce events. Evidence of a similar degree of wrist cocking during the backswing was present in both batting shots, generating a similar bat angle at the top of the backswing, while players raised their hands significantly higher in preparation for the pull shot. A proximal to distal sequencing of peak segmental velocities was apparent during the forward drive but not during the pull shot, suggesting different methods of generating bat speed in each case. Relationships were also found between the line of the delivery and both the stride length and type of follow through used by batsmen, with deliveries wide of off stump being associated with a longer stride and full follow through. Further interrogation of the data will allow for individual player assessment in a case study approach, allowing additional information on truly elite batsmen, and identify the most important factors and relationships for success.

Q2. What are the effects of impact location on batting shot outcome?

It is widely accepted amongst cricket players and coaches that impacts further from the sweetspot of the bat cause a reduction in ball speed, and a decrease in the accuracy of ball placement due to increased bat twist. Results from this study suggest that impacts occurring as little as 2 cm from the midline of the bat in its medio-lateral axis, or 5 cm from the sweetspot in the vertical plane, cause a reduction in post-impact ball speed of around 8% in comparison to an impact directly on the sweetspot. Impacts away from the midline of the bat in its medio-lateral plane have also been found to cause the bat to twist, and the ball to depart on an unintended trajectory, with an impact 2 cm from the midline being found to generate a peak angular velocity of the bat about its longitudinal axis of around $4000°s^{-1}$, causing the ball to depart approximately 13° away from the intended trajectory. This study not only highlights the small margin for error provided to a batsman hitting a cricket ball, but may also allow researchers a methodology for determining shot success without tracking post-impact ball trajectory.

Q3. How much movement variability is present in cricket batting, and how does it vary according to skill level and delivery method?

Previous research has not explored the issue of movement variability in cricket batting in any depth. Results from this study suggest the commencement of the downswing event to be a crucial time in the execution of both the forward drive and pull shots, as it displayed the lowest timing variability and the lowest variability in bat and upper limb angles for both skill level groups. Clear differences were found in terms of shot outcome and movement timings between delivery methods, suggesting variability in the static ball trials is significantly reduced. Kinematic variability was shown to consistently decrease to the point of impact in the static ball trials, while displaying a marked increase during the downswing in the bowling machine trials. This is indicative of batsman altering their movement patterns to adjust to the more variable inbound delivery, in order to gain a successful impact. Although only one significant difference was found between skill level groups; increased variability in the timing of the backwards weight transfer during the pull shot, inspection of the data suggests elite players to be more accurate in generating consistent shot outcomes than the amateur group. Further investigation of these data, perhaps with additional subjects, may reveal more significant trends between skill level groups.

Q4. What are the effects of facing different delivery methods on batsman response?

Previous researchers have identified a number of differences exhibited by batsman when facing a bowling machine compared to a bowler, although their results are often contradictory, use small samples of batsmen with ranging abilities, and often lack scientific rigour. The results of this study indicate that batsmen utilise fundamentally different techniques against each delivery methods, and call into question the validity of both the bowling machine and the Sidearm, in the way they are currently used, as providing an accurate and realistic representation of batting against a bowler. It is suggested that, while the pre-release knowledge of approximate ball bounce location afforded to the batsman when facing a bowling machine is the primary cause of differences compared to a bowler, the majority of differences found between the Sidearm trials, particularly in the unknown length condition, and the bowler trials were as a result of the significantly lower ball speed and longer release to impact time. It is therefore recommended that coaches attempt to avoid the over-use of the bowling machine, perhaps only using it to practice and implement more stable movement patterns, instead favouring the Sidearm, delivered from closer or with increased speed, due to its increased realism when compared to facing a bowler.

Q5. Which aspects of batting technique characterise the longest hitters in a range hitting task?

While the ability of a batsman to hit the ball large distances is becoming more important in the modern game, no research has investigated the technique characteristics exhibited by the longest hitters in cricket batting. Initially, two launch parameters were identified as crucial to generating large carry distances, with a high post-impact ball speed and a launch angle close to the optimum of 42° explaining between 92% and 99% of the variance in ball carry distance. Next, three parameters were identified which explained 70% of the variance in ball launch speed; impact location in the medio-lateral and vertical planes of the bat, and the pre-impact bat speed. This suggests that an impact location near the sweetspot of the bat and with a high pre-impact bat speed generates a higher post-impact ball launch speed. Finally, three technical parameters were identified as explaining 71% of the variance in bat speed, when considering only those trials with the highest ball launch speed. These parameters were; the maximum Z-factor (separation of the pelvis and thorax segments in the transverse plane) during the downswing, the amount of front elbow extension during the downswing, and the amount of wrist uncocking during the downswing. The results indicate that the longest hitters exhibit a larger maximum Z-factor, larger amounts of front elbow extension, and larger amounts of wrist uncocking during the downswing.

10.4 Future Studies

Additional research questions that are prompted by the work in this thesis include:

Q1. What are the effects of changing the characteristics of a delivery, for example the ball speed and bounce location, on the technique used by a batsman when executing a given shot?

Although detailed kinematic descriptions of the forward drive and pull shots have been presented here (Chapter 5), these simply used mean and standard deviation values measured across all trials conducted. It would be interesting to take this analysis one step further, and investigate how key kinematic variables, such as the backswing height and stride length, change according to the speed and bounce location of the ball.

Q2. To what extent do the characteristics of the bat and its design affect the amount by which an off-centre impact influences shot outcome?

Having investigated in detail the relationships between impact location and post-impact ball speed and direction (Chapter 6), it would be interesting to assess the effects of different bat designs on these relationships. Further assessment would investigate the effects of bat mass as well as inertial characteristics on post-impact ball speed and direction, as well as the bat's resistance to twisting. This would allow a greater understanding of the potential benefits of different bat designs in generating greater hitting performance.

Q3. Do elite batsmen display higher or lower kinematic variability than amateur players when executing a given batting shot against a Sidearm or bowler?

Although only an initial study into movement variability has been conducted here (Chapter 7), it is clear that differences between professional and high level amateur batsmen are hard to identify under the static ball and bowling machine conditions. It is hypothesised that, under the more random hitting conditions when facing a Sidearm or bowler, the true difference in skill level and performance would be revealed, and a greater understanding of the mechanisms by which professional batsmen generate more consistently successful impacts would be discovered.

Q4. Would an increase in the speed of Sidearm deliveries allow batsmen to more closely replicate the technique displayed against a real life bowler?

Through an investigation of the differences in batsman response when facing different delivery methods, Chapter 8 suggested that while differences in response between the bowling machine and bowler trials was largely a result of the batsman's pre-release knowledge of ball bounce location, differences between the Sidearm and bowler trials was likely a consequence of the lower ball speed and longer reaction times afforded to the batsman when facing the Sidearm. This led to the recommendation of coaches either increasing the speed, or decreasing the distance between batsman and thrower, when using the Sidearm, to increase the realism of the delivery to that of a bowler. It would be interesting to investigate the effects of this on batsman response, both in comparison to a bowler, and the original Sidearm condition as performed in this study.

Q5. What aspects of batting technique characterize those players who consistently generate successful impacts close to the sweetspot of the bat?

Although Chapter 9 has identified some of the key technical parameters in generating large carry distances during a range hitting task, this study gives no indication into the consistency of success of each player and the technical parameters associated with reliable shot outcomes. It is hypothesised that players who generate a bat path passing through the line of the ball for the longest period of time, thus giving themselves the largest margin for error in terms of timing their shot, are more likely to generate consistently successful impact locations towards the sweetspot of the bat, and thus consistently successful shot outcomes. It would be interesting to investigate this in more detail, as to achieve optimal performance batsmen must be able to generate successful shot outcomes on a consistent basis, while also utilising the techniques identified in this study to generate large carry distances

Q6. Would a study conducted on a turf wicket have produced the same findings as those found on an artificial surface?

This study, in its entirety, has been carried out using an artificial indoor batting surface. While this is designed to as closely as possible replicate batting on a turf wicket, there are no doubt a number of differences between these two conditions. It would be interesting to examine in the same level of detail, the performance of batsmen while batting on a turf wicket, in an attempt to identify in particular differences in kinematic response when batting on the two surfaces. While a study of batsmen in match conditions would further enhance the realism of their responses, it would be difficult to generate the same level of detail in the data, and the repetition of shots required for these analyses, in this environment.

10.5 Limitations

Although this study can be seen as an overall success, there are a number of limitations present throughout the methodology and analysis. As with many studies of elite populations, the small sample sizes used throughout this research provide one of the major limitations to this work. With larger sample sizes it may have been possible to discover additional significant differences between groups, and generalize findings more towards the whole population, however due to player availability this was not possible. Equally, while the practice facility used for data collection is as realistic to an outdoor wicket as possible, the nature of an indoor surface changes that characteristics of ball bounce slightly, and may have affected batsman response in some way. Finally, the relatively low number of trials captured for the bowler and Sidearm delivery methods is a slight limitation. Due to the substantially decreased accuracy provided by each of these, trials where the correct shot was played were harder to achieve. Due to time pressures, it was not possible to capture additional data for these delivery methods, perhaps proving a limitation with some of the findings in this study.

10.6 Conclusions

The aim of the present study was to develop a methodology by which the three-dimensional kinematics of a batsman could be captured in a realistic training environment, and utilise this to answer a series of research questions. The methodology was developed and validated using a number of different checks. It proved successful in terms of its ease to implement with elite and amateur players, and the wealth of data it produced. To answer the research questions, a biomechanical model was developed and applied to the kinematic data for a series of batting shots performed by elite and amateur batsmen. Again, this model proved to be highly useful in producing the necessary data to answer each of the research questions posed, as well as displaying the potential to provide data to answer several more. A number of interesting conclusions have been drawn as a result of these analyses, providing a base from which further cricket batting research can be conducted.

REFERENCES

Abernethy, B. (1990) 'Anticipation in squash: Differences in advance cue utilization between expert and novice players', *Journal of Sports Sciences*, 8(1), pp. 17-34.

Abernethy, B. (1988) 'The effects of age and expertise upon perceptual skill development in a racquet sport', *Research Quarterly for Exercise and Sport,* 59(3), pp. 210-221.

Abernethy, B. (1981) 'Mechanisms of skill in cricket batting', *Australian Journal of Sports Medicine,* 13(0045-0650), pp. 3-10.

Abernethy, B., Gill, D.P., Parks, S.L. and Packer, S.T. (2001) 'Expertise and the perception of kinematic and situational probability information', *Perception,* 30(2), pp. 233-252.

Abernethy, B. and Russell, D.G. (1987) 'Expert-novice differences in an applied selective attention task', *Journal of Sport Psychology,* 9(4), pp. 326-345.

Abernethy, B. and Russell, D.G. (1984) 'Advance cue utilisation by skilled cricket batsmen', *Australian Journal of Science and Medicine in Sport,* 16(2), pp. 2-10.

Abernethy, B., Zawi, K. and Jackson, R.C. (2008) 'Expertise and attunement to kinematic constraints', *Perception,* 37(6), pp. 931-948.

Arutyunyan, G.A., Gurfinke, V.S. and Mirskii, M.L. (1968) 'Investigation of aiming at a target', *Biophysics - USSR,* 13(3), pp. 642.

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

Bartlett, R., Wheat, J. and Robins, M. (2007) 'Is movement variability important for sports biomechanists?', *Sports Biomechanics,* 6(2), pp. 224-243.

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

Bernstein, N.A. (1967) *The co-ordination and regulation of movements.* 1st edn. Oxford: Pergamon Press Ltd.

Betzler, N.F., Monk, S.A., Wallace, E.S. and Otto, S.R. (2012) 'Variability in clubhead presentation characteristics and ball impact location for golfers' drives', *Journal of Sports Sciences,* 30(5), pp. 439-448.

Bootsma, R.J. and Van Wieringen, P.C. (1990) 'Timing an attacking forehand drive in table tennis.', *Journal of Experimental Psychology: Human Perception and Performance,* 16(1), pp. 21.

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

Bradshaw, E.J., Keogh, J., Hume, P.A., Maulder, P.S., Nortje, J. and Marnewick, M. (2009) 'The effect of biological movement variability on the performance of the golf swing in high- and low-handicapped players', *Research Quarterly for Exercise and Sport,* 80(2), pp. 185-196.

Broderick, M.P. and Newell, K.M. (1999) 'Coordination patterns in ball bouncing as a function of skill', *Journal of Motor Behaviour,* 31(2), pp. 165-188.

Carlton, L.G. (1992) 'Visual processing time and the control of movement', *Advances in Psychology,* 85, pp. 3-31.

Cheetham, P.J., Martin, P.E., Mottram, R.E. and 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, pp. 192-199.

Chin, A., Elliott, B., Alderson, J.A., Lloyd, D. and Foster, D. (2009) 'The off-break and "doosra": Kinematic variations of elite and sub-elite bowlers in creating ball spin in cricket bowling', *Sports Biomechanics,* 8(3), pp. 187-198.

Chu, Y., Sell, T. and Lephart, S. (2010) 'The relationship between biomechanical variables and driving performance during the golf swing', *Journal of Sports Sciences,* 28(11), pp. 1251-1259.

C-Motion (2015) *IK Kinematic Foot - Visual 3D Wiki Documentation.* Available at: http://www.c-motion.com/v3dwiki/index.php/IK_Kinematic_Foot (Accessed: 18/02/2016).

C-Motion (2014) *Segment Properties - Visual 3D Wiki Documentation.* Available at: http://www.c-motion.com/v3dwiki/index.php/Segment_Properties (Accessed: 18/02/2016).

Cohen, R.G. and Sternad, D. (2009) 'Variability in motor learning: relocating, channelling and reducing noise', *Experimental Brain Research,* 193(1), pp. 69-83.

Coleman, S. and Rankin, A.J. (2005) 'A three-dimensional examination of the planar nature of the golf swing', *Journal of Sports Sciences,* 23(3), pp. 227-234.

Cooper, M.A.J. and Mather, J.S.B. (1994) *Categorisation of golf swings.* In A.J. Cochran & M.R. Farrally (Eds.), *Science & Golf II: Proceedings of the 1994 World Scientific Congress of Golf* (pp. 65 – 70) London: Taylor & Francis.

Cork, A., Justham, L. and 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), pp. 201-208.

Craig, C.M., Goulon, C., Berton, E., Rao, G., Fernandez, L. and Bootsma, R.J. (2009) 'Optic variables used to judge future ball arrival position in expert and novice soccer players', *Attention, Perception, & Psychophysics,* 71(3), pp. 515-522.

Croft, J. and Button, C. (2009) *Visual search strategies of cricket batsmen.* Auckland: SPARC.

Croft, J.L., Button, C. and Dicks, M. (2009) 'Visual strategies of sub-elite cricket batsmen in response to different ball velocities', Human Movement Science, 29(5), pp. 751-763.

Dias, G.R. and Ferdinands, R. (2010) *The biomechanics of the initial movement in cricket batting. In Conference of Science, Medicine, & Coaching in Cricket, 2010*. 1-3 June. Cricket Australia, pp. 63-66.

ECB (2009) *1st4Sport ECB Level 3 Manual in Coaching Cricket.*

Egret, C.I., Nicolle, B., Dujardin, F.H., Weber, J. and Chollet, D. (2005) 'Kinematic analysis of the golf swing in men and women experienced golfers', *International Journal of Sports Medicine,* 27(06), pp. 463-467.

Elliott, B. (2006) 'Biomechanics and tennis', *British Journal of Sports Medicine,* 40(5), pp. 392-396.

Elliott, B., Baker, J. and 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), pp. 48-54.

Elliott, B.C., Alderson, J.A. and Denver, E.R. (2007) 'System and modelling errors in motion analysis: implications for the measurement of the elbow angle in cricket bowling', *Journal of Biomechanics,* 40(12), pp. 2679-2685.

Escamilla, R.F., Fleisig, G.S., DeRenne, C., Taylor, M.K., Moorman III, C.T., Imamura, R., Barakatt, E. and Andrews, J.R. (2009b) 'Effects of bat grip on baseball hitting kinematics', *Journal of Applied Biomechanics,* 25(3), pp. 203-209.

Escamilla, R.F., Fleisig, G.S., DeRenne, C., Taylor, M.K., Moorman III, C.T., Imamura, R., Barakatt, E. and Andrews, J.R. (2009a) 'A comparison of age level on baseball hitting kinematics', *Journal of Applied Biomechanics,* 25(3), pp. 210-218.

Farrow, D. and Abernethy, B. (2003) 'Do expertise and the degree of perception-action coupling affect natural anticipatory performance?', *Perception,* 32(9), pp. 1127-1140.

Farrow, D. and Abernethy, B. (2002) 'Can anticipatory skills be learned through implicit video based perceptual training?', *Journal of sports sciences,* 20(6), pp. 471-485.

Fleisig, G., Chu, Y., Weber, A. and Andrews, J. (2009) 'Variability in baseball pitching biomechanics among various levels of competition', *Sports Biomechanics,* 8(1), pp. 10-21.

Fleisig, G., Nicholls, R., Elliott, B. and Escamilla, R. (2003) 'Tennis: Kinematics used by world class tennis players to produce high-velocity serves', *Sports Biomechanics,* 2(1), pp. 51-64.

Franks, I.M., Weicker, D. and Robertson, D.G.E. (1985) 'The kinematics, movement phasing and timing of a skilled action in response to varying conditions of uncertainty', *Human Movement Science,* 4(2), pp. 91-105.

Gibson, A.P. and 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), pp. 3-6.

Glazier, P., Davids, K., Renshaw, I. and Button, C. (2005) 'Uncovering the secrets of The Don', *Sport Health,* 22, pp. 16-21.

Glazier, P. (2011) 'Movement variability in the golf swing: Theoretical, methodological, and practical issues', *Research quarterly for exercise and sport,* 82(2), pp. 157-161.

Golby, J. (1989) 'The relative importance of perceptual information throughout the sections of a cricket ball’s trajectory', *Current Psychology*, 8(3), pp. 188-199.

Goulet, C., Bard, C. and Fleury, M. (1989) 'Expertise differences in preparing to return a tennis serve: a visual information processing approach', *Journal of Sport & Exercise Psychology,* 11, pp. 382-398.

Gray, R. (2009) 'Intercepting moving objects: Fundamental principles learned from baseball', *Reviews of human factors and ergonomics,* 5(1), pp. 114-139.

Gray, R. (2002) 'Behaviour of college baseball players in a virtual batting task.', *Journal of Experimental Psychology: Human Perception and Performance,* 28(5), pp. 1131.

Gray, R. and Regan, D. (1998) 'Accuracy of estimating time to collision using binocular and monocular information', *Vision research,* 38(4), pp. 499-512.

Haake, S.J., Carre, M.J. and Goodwill, S.R. (2003) 'The dynamic impact characteristics of tennis balls with tennis rackets', *Journal of Sports Sciences,* 21(10), pp. 839-850.

Hamill, J., van Emmerik, R., Heiderscheit, B. and Li, L. (1999) 'A dynamical systems approach to lower extremity running injuries', *Clinical Biomechanics,* 14(5), pp. 297-308.

Hau, A. (2013) *The effect of ball impact location on wrist flexion and extension, and pronation and supination angles for one-handed tennis forehand and backhand groundstrokes.* Undergraduate thesis (unpublished).

Hiley, M.J., Zuevsky, V.V. and Yeadon, M.R. (2013) 'Is skilled technique characterized by high or low variability? An analysis of high bar giant circles', *Human movement science,* 32(1), pp. 171-180.

Hocknell, A. (2002) 'High-performance driver design: benefits for all golfers', *Journal of Sports Sciences,* 20(8), pp. 643-649.

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

Hurrion, P. (2008) Batting is a side-on game - or at least it used to be. Coventry: Quintic.

James, C.R. (2004) 'Considerations of movement variability in biomechanics research', in Stergiou, N. (ed.) *Innovative Analyses of Human Movement*. 1st edn. Human Kinetics, pp. 29-62.

James, D.M., Carré, M.J. and Haake, S.J. (2004) 'The playing performance of county cricket pitches', *Sports Engineering,* 7(1), pp. 1-14.

Katsumata, H. (2007) 'A functional modulation for timing a movement: A coordinative structure in baseball hitting', *Human Movement Science,* 26(1), pp. 27-47.

Katsumata, H. and Russell, D.M. (2012) 'Prospective versus predictive control in timing of hitting a falling ball', *Experimental brain research,* 216(4), pp. 499-514.

Knudson, D. (1993) 'Effect of string tension and impact location on ball rebound accuracy in static tennis impacts', *Journal of Applied Biomechanics,* 9(2), pp. 143-148.

Knudson, D. (1991) 'Effect of string type and tension on ball vertical angle of rebound in static tennis impacts', *Journal of Human Movement Studies*, 20, pp. 39-47.

Koenig, G., Tamres, M. and Mann, R.W. (1994) *The biomechanics of the shoe-ground interaction in golf.* In A.J. Cochran & M.R. Farrally (Eds.), *Science & Golf II: Proceedings of the 1994 World Scientific Congress of Golf* (pp. 40) London: Taylor & Francis.

Körding, K.P. and Wolpert, D.M. (2004) 'Bayesian integration in sensorimotor learning', *Nature*, 427(6971), pp. 244-247.

Land, M.F. and McLeod, P. (2000) 'From eye movements to actions: how batsmen hit the ball', *Nature neuroscience,* 3(12), pp. 1340-1345.

Langdown, B.L., Bridge, M. and Li, F.X. (2012) 'Movement variability in the golf swing', *Sports Biomechanics,* 11(2), pp. 273-287.

Le Runigo, C., Benguigui, N. and Bardy, B.G. (2005) 'Perception-action coupling and expertise in interceptive actions', *Human movement science,* 24(3), pp. 429-445.

Lee, D.N. (1980) 'Visuo-Motor Coordination in Space-Time', *Advances in Psychology,* 1, pp. 281-295.

Lee, D.N. (1976) 'A theory of visual control of braking based on information about time-to-collision', *Perception,* 5(4), pp. 437-459.

Lee, D.N., Lishman, J.R. and Thomson, J.A. (1982) 'Regulation of gait in long jumping.', *Journal of Experimental Psychology: Human Perception and Performance*, 8(3), pp. 448.

Lee, D.N., Young, D.S., Reddish, P.E., Lough, S. and Clayton, T.M.H. (1983) 'Visual timing in hitting an accelerating ball', *The Quarterly Journal of Experimental Psychology,* 35(2), pp. 333-346.

Lephart, S.M., Smoliga, J.M., Myers, J.B., Sell, T.C. and 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), pp. 860-869.

Lu, T.W. and O'Connor, J.J. (1999) 'Bone position estimation from skin marker co-ordinates using global optimisation with joint constraints', *Journal of Biomechanics,* 32(2), pp. 129-134.

Mann, D. (2010) *Can your players see the ball? what a cricket coach needs to know about the eyes and vision of their players. In Conference of Science, Medicine, & Coaching in Cricket, 2010.* 1-3 June. Cricket Australia, pp. 98.

Mann, D.L., Abernethy, B. and Farrow, D. (2010) 'Action specificity increases anticipatory performance and the expert advantage in natural interceptive tasks', *Acta Psychologica,* 135(1), pp. 17-23.

Mann, D.L., Spratford, W. and Abernethy, B. (2013) 'The head tracks and gaze predicts: how the world's best batters hit a ball', *PloS one,* 8(3), pp. 1-11.

MCC (1987) *The MCC Cricket Coaching Book.* 5th edn. London: The Kingswood Press.

Mcintyre, D.R. and Pfautsch, E.W. (1982) 'A kinematic analysis of the baseball batting swings involved in opposite-field and same-field hitting', *Research Quarterly for Exercise and Sport,* 53(3), pp. 206-213.

McKellar, D.K., Nurick, G.N. and Stretch, R.A. (1998) 'The measurement of the position of a ball striking a cricket bat', *The Engineering of Sport: Design and Development,* 1, pp. 275-282.

McLean, J. (1992) 'Widen the gap', Golf Magazine, 12, pp. 49-53.

McLeod, P. (1987) 'Visual reaction time and high-speed ball games', *Perception,* 16(1), pp. 49-59.

McRobert, A. and Tayler, M. (2005) 'Perceptual abilities of experienced and inexperienced cricket batsmen in differentiating between left and right hand bowling deliveries', *Journal of Sports Sciences,* 23(2), pp. 190-191.

Mitchell, S.R., Jones, R. and King, M. (2000) 'Head speed vs. racket inertia in the tennis serve', *Sports Engineering,* 3(2), pp. 99-110.

Moré, J.J. and Sorensen, D.C. (1983) 'Computing a trust region step', *SIAM Journal on Scientific and Statistical Computing,* 4(3), pp. 553-572.

Müller, S. and Abernethy, B. (2012) 'Expert anticipatory skill in striking sports: a review and a model', *Research Quarterly for Exercise and Sport,* 83(2), pp. 175-187.

Müller, S. and Abernethy, B. (2008) 'Validity and reliability of a simple categorical tool for the assessment of interceptive skill', *Journal of Science and Medicine in Sport,* 11(6), pp. 549-552.

Müller, S. and Abernethy, B. (2006) 'Batting with occluded vision: An in situ examination of the information pick-up and interceptive skills of high-and low-skilled cricket batsmen', *Journal of Science and Medicine in Sport,* 9(6), pp. 446-458.

Müller, S., Abernethy, B. and Farrow, D. (2006) 'How do world-class cricket batsmen anticipate a bowler's intention?', *The Quarterly Journal of Experimental Psychology,* 59(12), pp. 2162-2186.

Müller, S., Abernethy, B., Reece, J., Rose, M., Eid, M., McBean, R., Hart, T. and Abreu, C. (2009) 'An in-situ examination of the timing of information pick-up for interception by cricket batsmen of different skill levels', *Psychology of Sport and Exercise,* 10(6), pp. 644-652.

Myers, J., Lephart, S., Tsai, Y., Sell, T., Smoliga, J. and Jolly, J. (2008) 'The role of upper torso and pelvis rotation in driving performance during the golf swing', *Journal of Sports Sciences,* 26(2), pp. 181-188.

Newell, K.M. and Corcos, D.M. (1993) 'Issues in variability and motor control', *Variability and Motor Control,* 1, pp. 1-12.

Paull, G. and Glencross, D. (1997) 'Expert perception and decision making in baseball.', *International Journal of Sport Psychology,* 28(1), pp. 35-56.

Penn, M.J. and Spratford, W. (2011) 'Are current coaching recommendations for cricket batting technique supported by biomechanical research?', *Sports Biomechanics,* 11(3), pp. 311-323.

Penrose, J.M.T. and Roach, N.K. (1995) 'Decision making and advanced cue utilisation by cricket batsmen', *Journal of Human Movement Studies,* 29(5), pp. 199-218.

Peploe, C., King, M.A. and Harland, A.R. (2014) 'The effects of different delivery methods on the movement kinematics of elite cricket batsmen in repeated front foot drives', *Procedia Engineering,* 72, pp. 220-225.

Pinder, R.A., Davids, K., Renshaw, I. and Araújo, D. (2011a) 'Manipulating informational constraints shapes movement reorganization in interceptive actions', *Attention, Perception, & Psychophysics,* 73(4), pp. 1-13.

Pinder, R.A., Renshaw, I. and Davids, K. (2009) 'Information-movement coupling in developing cricketers under changing ecological practice constraints', *Human Movement Science,* 28(4), pp. 468-479.

Pinder, R.A., Renshaw, I., Davids, K. and Kerhervé, H. (2011b) 'Principles for the use of ball projection machines in elite and developmental sport programmes', *Sports Medicine,* 41(10), pp. 793-800.

Preatoni, E., Ferrario, M., Donà, G., Hamill, J. and Rodano, R. (2010) 'Motor variability in sports: A non-linear analysis of race walking', *Journal of Sports Sciences,* 28(12), pp. 1327-1336.

Preatoni, E., Hamill, J., Harrison, A.J., Hayes, K., Van Emmerik, R., Wilson, C. and Rodano, R. (2013) 'Movement variability and skills monitoring in sports', *Sports Biomechanics,* 12(2), pp. 1-24.

Ranganathan, R. and Carlton, L.G. (2007) 'Perception-action coupling and anticipatory performance in baseball batting', *Journal of Motor Behaviour,* 39(5), pp. 369-380.

Ranson, C., King, M., Burnett, A., Worthington, P. and Shine, K. (2009) 'The effect of coaching intervention on elite fast bowling technique over a two-year period', *Sports Biomechanics,* 8(4), pp. 261-274.

Ranson, C.A., Burnett, A.F., King, M., Patel, N. and O'Sullivan, P.B. (2008) 'The relationship between bowling action classification and three-dimensional lower trunk motion in fast bowlers in cricket', *Journal of Sports Sciences,* 26(3), pp. 267-276.

Regan, D. (1992) 'Visual judgements and misjudgements in cricket and the art of flight', *Perception,* 21, pp. 91-115.

Renshaw, I. and Fairweather, M.M. (2000) 'Cricket bowling deliveries and the discrimination ability of professional and amateur batters', *Journal of Sports Sciences,* 18(12), pp. 951-957.

Renshaw, I., Oldham, A.R., Davids, K. and Golds, T. (2007) 'Changing ecological constraints of practice alters coordination of dynamic interceptive actions', *European Journal of Sport Science,* 7(3), pp. 157-167.

Robertson, D.G.E. and Dowling, J.J. (2003) 'Design and responses of Butterworth and critically damped digital filters', *Journal of Electromyography and Kinesiology,* 13(6), pp. 569-573.

Robertson, G., Caldwell, G., Hamill, J., Kamen, G. and Whittlesey, S. (2013) *Research methods in biomechanics.* 2nd edn. Human Kinetics.

Robinson, R.L. (1994) *A study of the correlation between swing characteristics and club head velocity.* E & FN Spon London, pp. 84.

Sarpeshkar, V. and Mann, D.L. (2011) 'Biomechanics and visual-motor control: how it has, is, and will be used to reveal the secrets of hitting a cricket ball', *Sports Biomechanics,* 10(4), pp. 306-323.

Sarpeshkar, V., Mann, D.L., Spratford, W. and Abernethy, B. (2015) 'The influence of swing on the timing and coordination of a front-foot defensive shot among cricket batters across skill and age', *Proceedings of the World Congress of Science and Medicine in Cricket,* (5), pp. 95.

Savelsbergh, G.J., Whiting, H.T. and Bootsma, R.J. (1991) 'Grasping tau.', *Journal of Experimental Psychology: Human Perception and Performance,* 17(2), pp. 315.

Schmidt, R., Disselhorst-Klug, C., Silny, J. and Rau, G. (1999) 'A marker-based measurement procedure for unconstrained wrist and elbow motions', *Journal of Biomechanics,* 32(6), pp. 615-621.

Schmidt, R.A. and Lee, T.D. (2005) *Motor control and learning: A behavioural emphasis.* Human Kinetics Publishers.

Šenk, M. and Cheze, L. (2006) 'Rotation sequence as an important factor in shoulder kinematics', *Clinical Biomechanics,* 21, pp. 3-8.

Shaffer, B., Jobe, F.W., Pink, M. and Perry, J. (1993) 'Baseball batting: an electromyographic study.', *Clinical Orthopaedics and Related Research,* 292, pp. 285-293.

Shibayama, H. and Ebashi, H. (1983) 'Development of a motor skill using the golf swing from the viewpoint of the regulation of muscle activity', *Biomechanics VIII,* 1, pp. 895-902.

Shim, J., Carlton, L.G., Chow, J.W. and Chae, W.S. (2005) 'The use of anticipatory visual cues by highly skilled tennis players', *Journal of Motor Behaviour,* 37(2), pp. 164-175.

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

Stretch, R.A., Bartlett, R. and Davids, K. (2000) 'A review of batting in men's cricket', *Journal of Sports Sciences,* 18(12), pp. 931-949.

Stretch, R.A., Nurick, G.N., Balden, V. and McKellar, D.K. (2004) 'The position of impact of a ball striking a cricket bat: assisting coaches with performance analysis of cricket technique and skill levels.', *International Journal of Performance Analysis in Sport,* 4(2), pp. 74-81.

Stretch, R., Buys, F. and Viljoen, G. (1995) 'The kinetics of the drive off the front foot in cricket batting: hand grip force', *SA Journal for Research in Sport,* 18(2), pp. 83–93.

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

Symes, A.W. (2006) *The effect of mass distribution on cricket bat playing properties.* PhD thesis (unpublished).

Taliep, M.S., Galal, U. and Vaughan, C.L. (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), pp. 345-360.

Tenenbaum, G., Levy-Kolker, N., Sade, S., Liebermann, D. and Lidor, R. (1996) 'Anticipation and confidence of decisions related to skilled performance.', *International Journal of Sport Psychology,* 27, pp. 293-307.

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

Tyldesley, D. and Whiting, H. (1975) 'Operational timing.', *Journal of Human Movement Studies,* 1(4), pp. 172-177.

Vicon (2012a) *Plug-in-gait marker placement.* Available at: http://www.vicon.com/support (Accessed: 24/05/2013).

Vicon (2012b) *Vicon golfer model.* Available at: http://www.vicon.com/support/ (Accessed: 24/05/2013).

Wallace, E.S., Graham, D. and 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.* E & FN Spon London, pp. 25.

Warren, W.H., Young, D.S. and Lee, D.N. (1986) 'Visual control of step length during running over irregular terrain.', *Journal of Experimental Psychology: Human Perception and Performance,* 12(3), pp. 259.

Webster, J. and Roberts, J. (2011) 'Determining the effect of cricket leg guards on running performance', *Journal of Sports Sciences,* 29(7), pp. 749-760.

Weissensteiner, J., Abernethy, B. and Farrow, D. (2009) 'Towards the development of a conceptual model of expertise in cricket batting: A grounded theory approach', *Journal of Applied Sport Psychology,* 21(3), pp. 276-292.

Weissensteiner, J., Abernethy, B., Farrow, D. and Müller, S. (2008) 'The development of anticipation: a cross-sectional examination of the practice experiences contributing to skill in cricket batting', *Journal of Sport & Exercise Psychology,* 30(6), pp. 663.

Weissensteiner, J.R., Abernethy, B. and Farrow, D. (2011) 'Hitting a cricket ball: what components of the interceptive action are most linked to expertise?', *Sports Biomechanics,* 10(4), pp. 324-338.

Welch, C.M., Banks, S.A., Cook, F.F. and Draovitch, P. (1995) 'Hitting a baseball: a biomechanical description', *Journal of Orthopaedic and Sports Physical Therapy,* 22, pp. 193-201.

Wilson, C., Simpson, S.E., Van Emmerik, R. and Hamill, J. (2008) 'Coordination variability and skill development in expert triple jumpers', *Sports Biomechanics,* 7(1), pp. 2-9.

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

Woltring, H.J. (1995) 'Smoothing and differentiation techniques applied to 3-D data', *Three-dimensional analysis of human movement,* 1, pp. 79-99.

Woolmer, B. (2008) *The art and science of cricket.* 1st edn. Cape Town: Struik Publishers.

Worthington, P.J., King, M.A. and Ranson, C.A. (2013) 'Relationships Between Fast Bowling Technique and Ball Release Speed in Cricket', *Journal of Applied Biomechanics,* 29(1), pp. 78-84.

Wright, D.L., Pleasants, F. and Gomez-Meza, M. (1990) 'Use of advanced visual cue sources in volleyball.', *Journal of Sport & Exercise Psychology,* 12(4), pp. 406-414.

Wu, G., Van der Helm, F.C.T., Veeger, D., Makhsous, M., Van Roy, P., Anglin, C., Nagels, J., Karduna, A.R., McQuade, K. and Wang, X. (2005) 'ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion—Part II: shoulder, elbow, wrist and hand', *Journal of Biomechanics,* 38(5), pp. 981-992.

Yeadon, M.R. (1990) 'The simulation of aerial movement—II. A mathematical inertia model of the human body', *Journal of Biomechanics,* 23(1), pp. 67-74.

Yeadon, M.R. and King, M.A. (2015) 'The effect of marker placement around the elbow on calculated elbow extension during bowling in cricket', *Journal of Sports Sciences,* 33(16), pp. 1658-1666.

APPENDIX 1: CONSENT FORMS

PARTICIPANT INFORMATION SHEET

Investigating the Technical and Biomechanical Principles of Batting in Cricket

Adult Participant Information Sheet

Investigator Contact Details:
Chris Peploe – C.Peploe@lboro.ac.uk
Dr Mark King – M.A.King@lboro.ac.uk

What is the purpose of the study?
The aim of this research is to examine the technical and biomechanical factors that are associated with skilled batting in cricket

Who is doing this research and why?
This study is part of a PhD research project examining the biomechanics batting in cricket conducted by the Sports Technology and Sports Biomechanics research groups

Are there any exclusion criteria? The participants will be experienced cricket batsmen of at least a university level, free from injury.

What will I be asked to do?
The participant will be asked to be fitted with reflective markers and perform a range of batting shots against different delivery methods while being captured by the 3D motion capture system and high-speed video cameras

Once I take part, can I change my mind?
Yes! After you have read this information and asked any questions you may have we will ask you to complete an Informed Consent Form, however if at any time, before, during or after the sessions you wish to withdraw from the study please just contact the main investigator. You can withdraw at any time, for any reason and you will not be asked to explain your reasons for withdrawing.

What personal information will be required from me?
A general health information sheet will be collected at the beginning of the study.

Are there any risks in participating?
None of the requirements of this research study will exceed those of a normal training session, so risks are minimal.

Will my taking part in this study be kept confidential?
All data collected in this study will remain confidential and secure. Participants will be allocated an identification number for recording and storage of data, and no participant will be referred to by name outside of data collection sessions, such as in publication of the study.

What will happen to the results of the study?
All data collected conform to the university's guidelines on data collection and storage, and will therefore be stored securely in its original state for the duration of the collection, analysis and publication of the study.

Is there anything I need to bring with me?
You should bring your own batting equipment including personal protective equipment, pads, thigh pads, gloves, helmet, and bat.

What type of clothing should I wear?
Reflective motion markers will be placed on the skin, therefore shorts will be required for all testing sessions to allow placement of markers on the hip, trunk, and leg areas.

What do I get for participating?
Participants will be allowed ongoing feedback on batting performance throughout the time of the study; however, a detailed biomechanical analysis of batting performance will not be available until the research is completed.

I have some more questions; who should I contact?
Any questions regarding the testing procedures or batting practice should be first addressed to Chris Peploe (C.Peploe@lboro.ac.uk); alternatively, further queries may be addressed to Dr Mark King listed above.

If you have any concerns regarding your participation in this study, or the conduct of any of the investigators involved, please refer to the university policy relating to research misconduct at the following link:

http://www.lboro.ac.uk/admin/committees/ethical/Whistleblowing(2).htm.

INFORMED CONSENT FORM

- Please read this form and sign it once that you have understood the protocol as explained by the test coordinator.
- I voluntarily agree to take part in the October 2014 batting 3D testing day.
- I understand that the information about me recorded during the testing day will be stored securely and any resulting information will only be sent to me or any relevant coaches.
- I understand that all procedures have been approved by the Loughborough University Ethical Approvals (Human Participants) Sub-Committee.
- I agree to comply with the reasonable instructions of the supervising coach and will notify him/her immediately of any unexpected unusual symptoms or deterioration of health.
- I confirm that I have disclosed relevant medical information before the testing day.
- I understand that I have the right to withdraw from this study at any stage for any reason, and that I will not be required to explain my reasons for withdrawing.
- The screening will require sensors to be placed on the upper body and therefore it may be required for me to bat without a shirt.

Name: ……………………………………………**Date of Birth**………………………

Email Address……………………………………………………………………….

Signature: ……………………………………………… **Date:** ………………………

Signature of investigator: ………………………………………………………..

HEALTH SCREEN QUESTIONNAIRE

As a volunteer participating in a research study, it is important that you are currently in good health and have had no significant medical problems in the past. This is (i) to ensure your own continuing well-being and (ii) to avoid the possibility of individual health issues confounding study outcomes.

Please complete this brief questionnaire to confirm your fitness to participate:

1. At present, do you have any health problem for which you are:

(a)	On medication, prescribed or otherwise	Yes	☐	No	☐
(b)	Attending your general practitioner	Yes	☐	No	☐
(c)	On a hospital waiting list	Yes	☐	No	☐

2. In the past two years, have you had any illness which required you to:

(a)	Consult your GP	Yes	☐	No	☐
(b)	Attend a hospital outpatient department	Yes	☐	No	☐
(c)	Be admitted to hospital	Yes	☐	No	☐

3. Have you ever had any of the following:

(a)	Convulsions/epilepsy	Yes	☐	No	☐
(b)	Asthma	Yes	☐	No	☐
(c)	Eczema	Yes	☐	No	☐
(d)	Diabetes	Yes	☐	No	☐
(e)	A blood disorder	Yes	☐	No	☐
(f)	Head injury	Yes	☐	No	☐
(g)	Digestive problems	Yes	☐	No	☐
(h)	Heart problems	Yes	☐	No	☐
(i)	Problems with bones or joints	Yes	☐	No	☐
(j)	Disturbance of balance/coordination	Yes	☐	No	☐
(k)	Numbness in hands or feet	Yes	☐	No	☐
(l)	Disturbance of vision	Yes	☐	No	☐
(m)	Ear / hearing problems	Yes	☐	No	☐
(n)	Thyroid problems	Yes	☐	No	☐
(o)	Kidney or liver problems	Yes	☐	No	☐
(p)	Allergy to nuts	Yes	☐	No	☐

4. Has any, otherwise healthy, member of your family under the age of 35 died suddenly during or soon after exercise? Yes ☐ No ☐

If YES to any question, please describe briefly if you wish (e.g. to confirm problem was/is short-lived, insignificant or well controlled):

5. Allergy Information

(a)	Are you allergic to any food products?	Yes	☐	No	☐
(b)	Are you allergic to any medicines?	Yes	☐	No	☐
(c)	Are you allergic to plasters?	Yes	☐	No	☐

If YES to any of the above, please provide additional information on the allergy:

6. Please provide contact details of a suitable person for us to contact in the event of any incident or emergency.

Name:

Telephone Number:

Work ☐ Home ☐ Mobile ☐

Relationship to Participant:

7. Are you currently involved in any other research studies at the University or elsewhere?

Yes ☐ No ☐

If yes, please provide details of the study:

APPENDIX 2: LOWER BODY AND BAT DATA

LOWER BODY CALIBRATION DATA

Subject No.	Ankle Offset (°)	Knee Offset (°)	Hip Offset (°)
1	-1.2	11.2	-7.3
2	-3.1	1.6	-7.5
3	-3.9	13.1	-7.1
4	1.3	6.8	-6.5
5	-0.1	6.9	-3.3
6	9.4	-0.3	-5.3
7	11.8	-2.7	-3.9
8	4.4	-1.2	-2.6
9	2.4	5.5	-4.0
10	2.4	1.3	-2.5
11	10.0	-5.6	1.2
12	6.2	3.4	-0.2
13	1.8	5.1	-5.4
14	2.4	0.9	-3.1
15	3.7	1.6	-5.6
16	7.9	-2.1	0.8
17	5.1	0.3	-4.9
18	-2.2	9.8	-7.6
19	4.3	2.5	-5.6
20	-0.8	10.2	-6.3
21	0.9	7.7	0.6
22	-2.7	11.9	-8.1
23	3.2	2.4	-4.0
24	4.7	-0.1	-3.4
25	8.0	-3.2	-7.5
26	6.6	1.6	-6.2
27	-1.5	9.0	-2.7
28	2.4	3.2	-2.8
29	7.1	-0.5	-8.0
30	1.0	4.4	-2.3
31	-1.3	6.9	-6.1
Mean	2.9	3.6	-4.4
St. Dev.	4.1	4.8	2.7

BAT MEASUREMENTS

Sub. No.	Manufacturer	Model	Weight	Size	Mass	Total Length	Handle Length	Blade Length	Blade Width Top	Blade Width Middle	Blade Width Toe	Average Blade Width	COM from Toe	COM as % of Blade Length	COM Depth	Scale (40mm bar)	COM Depth
			lbs		*kg*	*mm*	*mm*	*mm*	*mm*	*mm*	*mm*	*mm*	*mm*	*% from toe*	*pixels*	*pixels/mm*	*mm from face*
12	Gray Nicholls	Oblivion LE	2'9	SH	1.12	855	295	560	109	108	108	108	348	62.1	202	7	29
13	Ton	Max Power	2'10	SH	1.203	850	295	555	107	108	107	107	361	65.0	152	5.3	29
14	GM	Epic DXM	2'9	SH	1.048	850	300	550	107	109	109	108	348	63.3	148	5.8	26
15	Nike	Drive	2'9	SH	1.095	860	290	570	107	108	106	107	370	64.9	162	6.4	25
16	GM	Epic DXM	2'9	SH	1.154	850	300	550	108	108	109	108	340	61.8	160	5.4	30
17	Gray Nicholls	Powerbow LE	2'9	SH	1.162	855	295	555	109	109	108	109	335	60.4	80	2.9	28
18	Simply Cricket	Silver Cobra	2'8	SH	1.024	850	300	550	107	106	107	107	351	63.8	125	4.7	27
19	BT Blades	Bomber	2'10	SH	1.112	840	290	550	108	108	108	108	342	62.2	131	5.2	25
20	Kingsport	Classic	2'8	SH	1.012	845	290	555	107	107	109	108	347	62.5	164	6.1	27
21	Kookaburra	Kahuna	2'8	SH	1.062	850	290	560	108	109	108	108	357	63.8	144	4.9	29
22	Kookaburra	Kahuna	2'10	SH	1.194	850	300	550	107	108	108	108	349	63.5	128	5.6	23
23	Onhand	Sapphire	2'9	SH	1.104	855	300	555	108	109	108	108	360	64.9	90	3.8	24
24	Nike	Drive	2'11	SH	1.254	850	290	560	108	108	109	108	340	60.7	148	5.4	27
25	Kookaburra	Kahuna	2'9	SH	1.108	850	300	550	108	109	108	108	365	66.4	160	6.2	26
26	Gray Nicholls	Ultimate E41	2'9	SH	1.141	855	295	560	106	108	107	107	350	62.5	121	4.2	29
27	Gray Nicholls	Oblivion E41	2'10	SH	1.195	849	298	551	107	106	106	106	345	62.6	138	5.1	27
28	Nike	Drive	2'8	SH	1.034	850	292	558	108	108	109	108	350	62.7	162	6.8	24
29	Gray Nicholls	Powerbow LE	2'8	SH	1.047	850	300	550	108	107	107	107	355	64.5	105	3.9	27
30	Spartan	Michael Clarke	2'9	SH	1.112	855	300	555	107	109	108	108	340	61.3	158	5.7	28
31	Gray Nicholls	Powerbow LE	2'8	SH	1.059	855	300	550	107	106	105	106	350	63.6	157	6.1	26
												Average	350.9	63.2		Average	26.7
												St Dev	10.3	1.7		St Dev	1.9

APPENDIX 3: BALL FLIGHT CURVE DERIVATION

CRICKET BALL DISPLACEMENT EQUATION

The cricket ball decelerates during flight (both pre- and post-impact), and can be expected to reach the batsman with 82 to 86% of its initial speed (James et al., 2004). Ground contact was not included in the time period for which curves were fit to the ball coordinate data in the present study and so any deceleration was due to air resistance acting on the ball. The drag force acting on a body is proportional to the squared velocity of that body and additionally, the deceleration of a body is proportional to the force acting on it (x: displacement; v: velocity; t: time):

$$v \cdot \frac{dv}{dx} = -k \cdot v^2$$
$$-\frac{dv}{v} = k \cdot dx$$
$$-\int_{v_0}^{v} \frac{dv}{v} = \int_0^x k \cdot dx,$$

where v_0 is the initial velocity at x = 0 (the beginning of the curve). Thus:

$$\ln(\frac{v_0}{v}) = k \cdot x$$
$$\frac{v_0}{v} = e^{kx}$$
$$v = v_0 \cdot e^{-kx}$$
$$\frac{dx}{dt} = v_0 \cdot e^{-kx}$$
$$\int_0^x e^{kx} \cdot dx = \int_0^t v_0 \cdot dt$$
$$\frac{1}{k}(e^{kx} - 1) = v_0 \cdot t$$
$$e^{kx} = 1 + k \cdot v_0 \cdot t.$$

Thus:

$$x = \frac{1}{k} \cdot \ln(1 + k \cdot v_0 \cdot t).$$

Differentiating this curve with respect to time gives the instantaneous velocity:

$$v = \frac{v_0}{1 + k \cdot v_0 \cdot t}.$$