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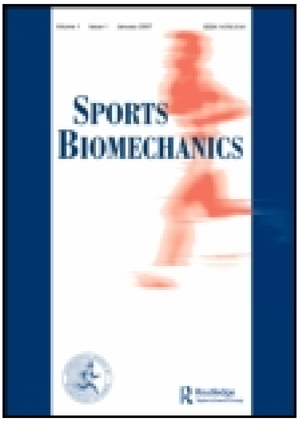


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# Biomechanics and visual-motor control: how it has, is, and will be used to reveal the secrets of hitting a cricket ball

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# Biomechanics and visual-motor control: how it has, is, and will be used to reveal the secrets of hitting a cricket ball

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**Abstract**
Cricket batting is an incredibly complex task which requires the coordination of full-body movements to successfully hit a fast moving ball. Biomechanical studies on batting have helped to shed light on how this intricate skill may be performed, yet the many different techniques exhibited by batters make the systematic examination of batting difficult. This review seeks to critically evaluate the existing literature examining cricket batting, but doing so by exploring the strong but often neglected relationship between biomechanics and visual-motor control. In three separate sections, the paper seeks to address (i) the different theories of motor control which may help to explain how skilled batters can hit a ball, (ii) strategies used by batters to overcome the (at times excessive) temporal constraints, and (iii) an interpretation from a visual-motor perspective of the prevailing biomechanical data on batting.

**Keywords:** *Hitting/batting, cricket, kinematics, motor control*

## Introduction

The ability of athletes to forcefully hit a ball with temporal precision is a remarkably refined skill which is developed over many years of practice, and demands the intricate coordination of the neuromuscular and visual systems. Not surprisingly, the astonishing skills of athletes in a variety of hitting sports such as tennis, baseball, and cricket have resulted in USA Today (2005) rating *hitting a ball* to be one of the *hardest things to do in sports*. Cricket batting provides an ideal task to examine the complexities of hitting a ball, particularly when seeking to understand performance at the temporal and spatial limits of human achievement. When batting, the player (a batter) often has $<600$ ms from the moment of ball release to judge the future arrival point of the ball (McLeod & Jenkins, 1991; Land & McLeod, 2000), and may be required to hit a ball within a temporal window as short as 2–5 ms to ensure optimal contact (Regan, 1992; Tresilian, 2004). Further, batters may need to contend with additional spatial constraints created as a result of a cricket ball adopting a curvilinear flight-path (*swing*, much like curve in baseball), and also by the ball laterally deviating off the playing surface after it has bounced on the ground (*seam* and *spin* bowlers will deliberately

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seek to do so to deceive the batter). The batter must overcome these constraints while exhibiting the fine motor control required to ensure that the ball is hit away from 11 opposing fielders. A multidisciplinary approach encompassing biomechanics and visual-motor control provides the potential to understand how such a remarkable feat is achievable, and ultimately to inform how these skills are best trained.

Skilled cricket batters produce complex, full-body movements to aid them in overcoming the demanding constraints inherent in the game, with the ultimate goal to produce the most forceful stroke possible to score runs. To contend with the potential deviations of the ball after it has bounced, a batter will typically either (i) step towards the ball to hit it immediately after it bounces close to the batter (i.e. a *front-foot* shot) or (ii) step back from the ball to hit it well after it has bounced, ensuring sufficient time is available to allow for any deviations in ball-flight to make optimal bat–ball contact (i.e. a *back-foot* shot; see Figure 1). When considering the force with which a ball is hit, full-body movements coordinating upper- and lower-body segments allow for a more effective transfer of forces to be summated into the hitting action.

Considering the popularity of the game of cricket across a considerable proportion of the world's population, there is a relative paucity of scientific research examining biomechanical and visual-motor behaviour integration in cricket batting. Sport scientists have found it difficult to isolate key elements common across batting techniques due to the wide variety of different techniques demonstrated by both skilled and lesser-skilled batters. Expert coaches have frequently supported this notion, supporting the supposition that there is no necessarily 'right' or 'wrong' way to bat, and that many of the greater players have exhibited techniques not necessarily commensurate with those recommended in coaching manuals (Conn, 2009). For example, Sir Donald Bradman (widely considered as the greatest batter of all time) exhibited a highly unique 'rotary' technique which is contrary to coaching convention and is yet to be replicated (Glazier et al., 2005).

Biomechanical investigations into cricket batting have made some important contributions in establishing benchmarks for the kinematic and kinetic properties for elements of batting across different levels of skill; however, in isolation, these studies generally fail to inform *why* these differences exist. Furthermore, there is little to inform coaches *how* this information can be used to inform and develop successful programmes to improve performance. There has also been a concurrent increase in the number of studies examining perception and visual-motor control in cricket batting with many studies making important contributions towards

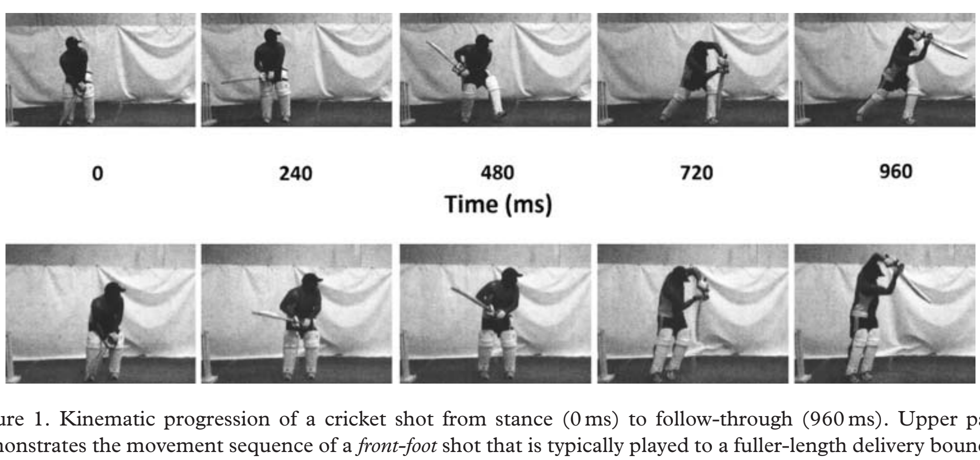


Figure 1. Kinematic progression of a cricket shot from stance (0 ms) to follow-through (960 ms). Upper panel demonstrates the movement sequence of a *front-foot* shot that is typically played to a fuller-length delivery bouncing near the batter. Lower panel demonstrates the movement sequence of a *back-foot* shot that is typically played to a shorter-length delivery bouncing further away from the batter.

understanding the strategies used by batters to overcome the temporal constraints of batting; however, they fall short of informing us *if* and *how* this information contributes to guide the movements of skilled batters. There is a clear need for a more multidisciplinary approach to better understand how and why skilled biomechanical movements are produced. In other words, the integration of findings from different scientific fields can provide additional meaning to the biomechanical data to achieve a higher level of understanding through the appreciation of the underlying processes involved in the planning, organisation, and execution of skilled movements. This approach is apparent in some of the more recent work in cricket batting (e.g. Müller & Abernethy, 2006; Weissensteiner, 2008; Mann et al., 2010b), consistent with recent (Phillips et al., 2010) and previous calls (Abernethy et al., 1993) for multidisciplinary work. The aim of this paper was to comprehensively review literature on (and relevant to) the task of cricket batting by focussing on the nexus between biomechanics and visual-motor control. The paper, presented in three sections, seeks to unite these two disparate scientific fields to highlight the interdependency that exists between the two and provide a unique perspective on how athletes are able to hit a ball. Section 1 examines the existing literature and perspectives on how the visual-motor system guides movements to be in the right place, at the right time, to hit an oncoming ball. Section 2 expands on this knowledge by examining the visual-motor strategies implemented by batters to overcome the temporal constraints to be placed in the right place, *in time*. Finally, Section 3 looks at the biomechanical movements that enable skilled batters to be in the right place, *in style*. It explores the kinematic and kinetic properties of the batting techniques of skilled batters, comparing results from the scientific literature with those advocated by some of the most influential coaching philosophies in cricket. This collective review of information outlines the complexities involved with hitting a ball and provides the basis for future work to enhance our knowledge and understanding of the underlying processes involved in hitting.



### *Being at the right place, at the right time: the visual-motor control of hitting*

*How do we control movement?* Successful hitting requires the performer to possess an efficient link between the perceptual and motor systems to ensure that precise information from both the opponent and the ball's flight-path is best used to adapt movements for optimal body-positioning and timing of the bat-swing to hit the ball. This coupling between perception and action forms a critical element of expertise; however, there is considerable debate on how the human body is capable of organising movements. There are two primary schools of thought for how skilled movements are controlled: *predictive control*, by which performers execute a highly reproducible motor programme at any given moment in time; and *prospective control*, by which performers produce a unique motor solution to any given situation which is constantly regulated in an 'online' manner (i.e. where movement is constantly regulated over time, see Montagne et al., 1999).

Predictive control proposed that the observable kinematic movement patterns of athletes (in this case batters) are the result of a predetermined motor programme which is well learned, organised prior to the execution of movement, and can be executed at a given point in time (Schmidt, 1975; Zelaznik, 1986). Tyldesley and Whiting (1975) proposed that for any given situation, the performer will select the most appropriate response from their repertoire of movements, following a predetermined motor programme to execute that movement. From this perspective, once an appropriate movement has been selected, and can be executed within a given amount of time, the key role of the batter is to initiate that movement at the precise time required to ensure that the ball is hit at the moment of arrival. This requires the batter to produce an extremely precise prediction of the exact time and location that the ball will arrive (hence a predictive type of control). In this sense, the movement can be considered analogous to a computer program that can simply be 'run' at any given moment in time. More recent iterations of this theory have allowed for scaling of all (or different elements of) movement to allow appropriate adjustments to be made (Schmidt & Lee, 2005). From a biomechanical standpoint, the variation seen between repeated trials of an identical movement is typically interpreted as being a result of system noise, or of measurement error.

The contrasting theory of motor control has suggested that no two movements are ever the same, and that no (or little) prediction is required to, in this case, successfully hit a ball. Bootsma and van Wieringen (1990) suggest that a complete reliance on consistent movement production is not feasible, and that a prospective strategy exercising real-time online alterations of movement is necessary for successful bat–ball interception. In their landmark study examining table-tennis players performing a series of similar attacking forehand shots, Bootsma and van Wieringen proposed that if a movement were to be initiated at a later point in time, this would require a faster acceleration prior to bat–ball contact. This funnelling of movement was found in a series of forehand shots, and reflects the relationship between the perceptual and motor systems in which updated information is made available for the perceptual and movement variables as the task unfolds over time, allowing appropriate modifications to be made to the task. These findings have been widely interpreted to suggest that athletes continuously alter their movements in an online manner (prospective control) to ensure optimal contact, rather than movement execution being the result of a pre-planned motor programme.

*Can we alter movement in an online fashion?* Any system that responds to a given stimulus must have some form of inherent delay: the *visual-motor delay* – the time taken for the motor system to respond to a visual stimulus – has for some time been a significant area of conjecture in the field of motor control. McLeod (1987) sought to establish the visual-motor delay, with skilled cricket batters attempting to hit balls which, in some cases, deviated after hitting ridges in the ground caused by wooden dowels placed under the playing surface. It was found that batters were unable to alter their shot within 200 ms of ball arrival. This result was interpreted to be an indication that the visual-motor delay was in the vicinity of 200 ms, though others have criticised this conclusion as it fails to take account of the considerable lag in time required to change the impulse (and hence direction) of a large wooden bat. Alternative studies have suggested that the visual-motor delay may be as low as 55–130 ms (see Lee et al., 1983; Bootsma & van Wieringen, 1990). When it is considered that ball-flight for a cricket delivery can be as short as 450 ms, and that there is a 200 ms visual-motor delay to change the direction of the bat, the control mechanism for cricket batting (and for most forms of hitting) is perhaps best conceptualised as a hybrid form of control between prospective and predictive mechanisms. It is likely that prospective control is achievable up to approximately 200 ms prior to bat–ball contact, after which the batter is required to have made some form of prediction for the future time and place that the ball will arrive (see Tresilian, 2005 for further evidence and discussion).

The idea that skilled batters may be unable to alter their movement within 200 ms of bat–ball contact may be incommensurate with anecdotal observations of the game; in particular, it is apparent that batters are able to alter (check) their shot mid-swing, and that fine adjustments of the wrists may be possible to provide fine control over ball direction. Anecdotally, a key skill of elite batters is a reported ability to manoeuvre the ball away from the opposing fielders using fine manipulations of the batter's wrist position. Sir Donald Bradman famously practiced his batting skills by using a cricket stump to repeatedly hit a golf ball against a corrugated iron tank (Fraser, 2009). It has been proposed that this style of training enabled Bradman to gain fine motor control of his wrists, which may have developed the ability to make fine online alterations at the wrist joint (Glazier et al., 2005). Findings from Dewhurst (1967) and Johansson and Westling (1984) support this notion by suggesting that it is possible to fine tune the distinct parameters of an existing motor programme without necessarily being required to change to a different motor programme to elicit the same response. Future work using kinematic tracking and electromyography (EMG) analyses of the batter's wrists will be useful to determine whether the wrist flexors and extensors can be finely manipulated to alter the execution of a shot. This will not only aid in clarifying the ability of skilled batters to make late shot adjustments but may also advocate similar forms of training to help develop the fine motor control of lesser-skilled or developing batters.

*How do we control movement when batting?* The ability of skilled cricket batters to account for the lateral deviations in ball-flight seen to occur either through the air, or as the ball bounces off the ground, is more easily explained and conceptualised using a prospective style of control. These deviations in flight-path will negatively impact on a batter's ability to predict the future arrival point of the ball, particularly considering that the magnitude of the deviations will vary according to environmental conditions and variations in playing surfaces. If control were to be predictive in this task, the batter would need to precisely predict the exact time and location that a deviating ball would arrive, yet evidence from other sports (e.g. soccer) suggests that the visual system is limited in its ability to anticipate the future arrival point of, in particular, a swinging ball (see Port et al., 1997; Craig et al., 2006, 2009). Athletes are consistently able to successfully intercept a curving ball though, suggesting that a more prospective type of control is better able to account for these, at times, unpredictable deviations in flight-path, at least up until approximately 200 ms prior to bat–ball contact. It is possible that batters manipulate the position of their wrists to adjust to the changes in the ball's flight-path upon interception to ensure sufficient bat–ball contact. Future work is required to help understand what the specific variations in the kinematics of movement may be when facing a swinging or deviating ball that enables batters to successfully hit the ball. Additionally, examinations into the gaze behaviours of batters, along with the measurement of the kinematic and kinetic properties against straight and curving deliveries, may help us to better understand the adaptations in batting techniques and the strategies implemented to promote successful interception.

An important area for future work lies in determining how the brain is capable of prospectively controlling movement based on vision of an approaching ball. If, as is increasingly believed, the brain does not perform calculations to predict the future location of arrival of the ball (see Montagne, 2005), then there must be some form of information that is used to directly guide the batter's movement. Considerable work has been performed across a wide variety of tasks to try to uncover the specific information used to directly control interception. Time-to-contact, or tau, has been a key variable proposed to be a critical part of directly perceiving information specific for movement (Lee et al., 1983). Tau provides fundamental information that is used to directly specify time-to-contact judgements by gathering optic information on the ball's relative expansion on the retina, rather than needing to calculate time-to-contact based on velocity and distance (see Savelsbergh et al., 1991; Tresilian, 1999). As a result, it is thought that the rate of object expansion on the retinal image directly guides the interceptive movements of the performer to be positioned in the required location at a specific point in time. Although an extensive body of literature has grown to examine the importance of tau, there also exists a counteracting sum of work which serves to question the usefulness of tau alone, suggesting that there may be a number of other equally useful factors used to determine time-to-contact (see Judge & Bradford, 1988; Heuer, 1993; Wann, 1996). Future examinations investigating the kinematics of batting against trials of different speeds, and for different locations of ball-bounce (i.e. differing lengths) may be useful in helping to determine how this information is used by batters to initiate bat downswing and ensure optimal timing. Furthermore, an examination of the kinematic movements of batters in response to alterations in the mass of the bat may help to better understand the specific sources of information used to derive time-to-contact information to initiate bat downswing.

*Being at the right place* in time*: overcoming the temporal constraints of batting*

*Anticipation*. Irrespective of the control mechanisms used to guide hitting, the temporal constraints placed on the batter are at times immense, and appropriate strategies are required to ensure that there is adequate time to successfully ensure bat–ball contact. One of the key strategies used by athletes (and specifically by cricket batters) to overcome these temporal constraints is through the effective identification and interpretation of advance kinematic information inherent in the movement of opponents. The development of these anticipatory skills provides batters with the ability to predict the outcome of a movement sequence produced by the opposing bowler *before* the ball is released, and as a result may aid in preparing movement coordination at an earlier point in time to facilitate successful bat–ball interception. In cricket, as in other interceptive sports such as tennis, badminton, and baseball, the batter learns to 'read' the specific kinematic movements of a bowler to predict the characteristics of the delivery being bowled. Investigations exploring the developmental histories of skilled batters suggest that the accuracy of a batter's ability to anticipate is most likely due to their exposure to bowlers across vast amounts of purposeful practice, and time spent in organised cricket (see Weissensteiner et al., 2008). Additionally, Côté (1999), Côté and Hay (2002), Côté et al. (2007) propose that during the sampling years of sporting development (typically 6–13 years of age), activities primarily focused on enjoyment and socialisation (such as backyard cricket) may be advantageous in developing anticipatory strategies, as the task constraints are often exaggerated with the distance between the batter and bowler being much closer than those encountered in organised sport. To date, however, the scientific literature fails to support this supposition, with anticipatory skill not being demonstrated until batters reach at least 15 years of age (see Weissensteiner et al., 2008).

The examination of gaze behaviour (eye movements) among skilled batters has helped to make inferences about the key sources of information which contribute to the effective anticipation of future events, and as a result, to successful hitting. Systems used to register the specific location that observers fixate their central vision have been used to show, for example, that when receiving a tennis serve, novice receivers are found to fixate on the body-segments more distal to the body centre of the opposing player (i.e. they focus on the hand and racquet). Conversely, expert players were found to produce a more definitive scan pattern which tended to first fixate on the movements of the trunk, the shoulder, and then the wrist to obtain optimal information about the stroke prior to moving fixation to the end effector (i.e. the racquet; see Abernethy & Russell, 1987; Singer et al., 1996). Based on the kinematic chain in which movement of more proximal segments precede those located more distally, it is inferred through the location of central vision that experts are able to anticipate future events at an earlier point in time by obtaining subtle pre-contact information from the more proximal segments moving earlier in the opponent's movement pattern.

Skilled cricket batters have demonstrated the ability to anticipate the type (e.g. the direction of swing and spin), and also the direction (or *line*), of an oncoming ball through the judicious observation of the kinematic movement patterns of the bowler prior to ball release (Abernethy & Russell, 1984; Penrose & Roach, 1995; Renshaw & Fairweather, 2000; Müller et al., 2006; Mann et al., 2010b). Müller et al. (2006) found that highly skilled batters were attuned to advance information from the bowler's hand, arm, and shoulder during the early period from the bowler's final back-foot impact prior to release, through to ball release. Additionally, highly skilled batters were able to make the above chance predictions on the bounce point of the ball when the relative motion of adjacent limbs (e.g. bowling arm) was simultaneously presented, as opposed to when the bowling hand was presented in isolation. Lesser-skilled batters were found to extract information primarily from the bowling hand, whereas skilled batters were found to make use of their prior knowledge and experience of the type of bowler to adopt a definitive search strategy by gathering subtle kinematic information from more locations (i.e. head, shoulders, bowling arm, trunk, and hips) to supplement the primary information derived from the bowling hand (see McRobert et al., 2009). As a result, the ability of skilled batters to identify earlier occurring visual cues is the result of a sophisticated and efficient scanning strategy to gather critical pieces of information from specific sources in the environment, and the improved accuracy in the interpretation of kinematic variances from the bowler culminates to promote successful performance (e.g. Müller et al., 2006; McRobert et al., 2009).

*How anticipation guides hitting*. One of the key limitations in the body of literature addressing skilled anticipation is that, although athletes are clearly able to anticipate at above-chance levels, there has been little indication for *if* and *how* this information is used to aid skilled movements. For the vast majority of studies examining anticipation, athletes have provided a verbal or written prediction of the outcome of a movement sequence observed on a video screen. Only recently have studies begun to demonstrate that this information is used by athletes to produce earlier movements (e.g. Shim et al., 2005), or to produce a more forceful response (Mann et al., 2010a). Studies examining the critical coupling between the perceptual and motor systems have found that batting behaviours are negatively affected by the removal of advance information, as experienced when batting against a ball-projection machine. Findings suggest that a significant decrease in the tight coupling between front-foot movements and bat-swing (e.g. Cork et al., 2010) is evident, and subsequently results in an inferior quality of hitting (see Pinder et al., 2009). These findings suggest that the coupling between perception and action is dependent on maintaining a naturalistic linkage between the two systems, as seen with the availability of advance information which affords anticipation when batting against a bowler *in situ*, and ensuring the preservation of the functional couplings between perception and action (Farrow & Abernethy, 2003). A further area of focus has been to examine whether the skills demonstrated at a conscious perceptual level reflect those seen when athletes perform movements in their natural environment. Mann et al. (2010b) examined the ability of skilled cricket batters to predict the direction of a ball bowled by an opposing bowler *in situ*, with batters required to do so verbally, with a shadowed movement, and when attempting to physically hit the ball. When asked to verbally predict ball direction, skilled batters were unable to do so at a level above that achievable by chance guessing. Only when they were able to move did the analysis of kinematic movements reveal that batters could predict ball -direction at levels above chance. Maximal performance was found when batters used a bat in an attempt to physically hit the ball. These results highlight the implicit nature of some motor skills: only when allowed to perform their well-learned hitting movement did athletes demonstrate the maximal ability to anticipate, and seemingly they did not have conscious awareness of how to verbally use the advance information to predict ball direction. This means that studies failing to incorporate movements may fail to capture the true essence of expertise in batting. A key direction for future work is to examine the kinematics and kinetics of skilled batters (potentially in conjunction with EMG) early in the hitting movements to examine how manipulations in the advance information influence early positional movements. It would be interesting to observe, for example, whether decoupling the bowler's kinematics from the type of delivery being bowled will force batters to reorganise their search strategies to derive more accurate and reliable information from other sources of the bowler's body. Studies of this nature will help to unravel how athletes use their superior anticipatory ability to overcome the temporal constraints they are faced with when batting.

Skilled batters have also been found to be better in using very early ball-flight information to predict the exact landing point of the ball. The examination of gaze behaviours whilst intercepting an approaching ball highlights the effective and efficient visual search strategy employed by skilled batters to obtain the information required to coordinate movement and overcome the temporal constraints of batting. At ball speeds commonly encountered by cricket batters (in excess of 25 m/s), batters visually track the initial 50–80% of ball-flight before making an anticipatory *saccade* (i.e. an eye movement in which gaze is shifted from one location to another; see Land & McLeod, 2000). The anticipatory saccade is believed to be produced at a sub-conscious level and is used to move central fixation forward to the predicted location where the ball will bounce. This saccade is produced based on the initial ball-flight information, and has been proposed to be a strategy to maintain fixation on a ball which is travelling at high speed throughout the duration of its flight-path. Although at this stage observed in a small sample size ($n = 3$) and against a ball projection machine, a key finding has been that this anticipatory saccade is produced earlier by skilled batters, enabling them to be placed in an optimal position to strike the ball at an earlier point in time when compared with lesser-skilled batters (i.e. they need less ball flight to predict landing position; see Land & McLeod, 2000). These findings represent a key element of expertise in hitting: skilled batters are better able to use early ball -flight information to predict the landing position of the ball, yet very little work has been done to follow-up on this intriguing study (though see Müller & Abernethy, 2006 for one exception). Little is known about the role of peripheral vision in guiding the hitting movement; this is a key limitation of current systems used to track eye movements as information can only be provided about where central vision is located, and about what may actually be attended to in the central or peripheral fields of vision. A key area for future work is to examine what may be a natural and crucial link between the visual search and kinematic movements of skilled batters. It is conceivable that one drives the other, or more likely that eye movements and kinematics work in a symbiotic relationship in which the two are coupled to perceive and move to be in the most favourable position to hit the ball as early as possible.

### *Being at the right place,* in style*: what kinematic and kinetic studies tell us about the movements of skilled batters*

Earlier studies examining the biomechanics of cricket batting have tended to be rather descriptive in nature, seeking to establish some of the key kinematic and kinetic tenants of batting. The rather redundant nature of motor organisation in batting, in which the same hitting outcome can be achieved by any number of different batting techniques, has made it difficult to find common biomechanical measures of success across different players, and across different levels of skill. More recent studies have begun to shed light on the nature of expertise in hitting by taking a different, and at times more methodical approach, including the use of within-participant designs (e.g. Thomlinson, 2009), and cross-sectional comparisons across skill-levels and age-groups (e.g. Weissensteiner, 2008). The aim of this section is to interpret the existing kinematic literature on cricket batting both from the perspective of visual-motor control, and in comparison with a number of key and influential coaching philosophies (e.g. Marylebone Cricket Club, 1987; Cricket Australia, 2005).

When examining striking in hitting sports, the chain of kinematic events promotes forces to be summated and transferred from the lower limbs through to the trunk, and further to the arms, where forces are then finally transferred to the implement striking the target. This notion is particularly evident among cricket batters performing an attacking stroke off their front foot (i.e. for a front-foot drive). When performing this shot, movement is initiated by advancing the front foot forward towards the location of ball-bounce to create a stable foundation, after which forces are transferred to the trunk, into the downswing of the bat, before finally transferring momentum to the ball being struck (see Figure 1, and Bartlett, 2007; Hede et al., 2010).

Examinations exploring cricket batting have primarily sought to understand the movement coordination of the front-foot drive. This is a common shot in cricket batting, by which the batter typically seeks to hit the ball straight past the bowler, usually in an aggressive manner. From a scientific standpoint, it has provided an ideal exemplar to examine batting as it maintains some common characteristics across different players, is moderately reproducible, and is predictably played when a ball bounces close to the batter. With the majority of studies exploring strokes off the front foot by a right-handed batter, except where expressed otherwise, the following section will refer to front-foot shots produced by a right-handed batter. The front-foot drive will be examined across five different phases as they would typically unfold chronologically: (i) batting stance, (ii) backlift of the bat in preparation for movement, (iii) initiation of front-foot movement and downswing of the bat, (iv) bat–ball contact, and (v) follow-through of the bat following bat–ball contact.

*Stance*. Common coaching philosophies advocate that batters should prepare their body for movement by maintaining an even distribution of weight across both feet to ensure stability, and to encourage the fast and efficient transfer of weight either forward or back to achieve a front- or back-foot stroke (e.g. Bradman, 1958; Tyson, 1994; Cricket Australia, 2005). In reality though, this may not actually be what happens for many batters. Stretch et al. (1998) found that provincial level batters tended to keep their front knee and hip directly over the front foot; the back knee, hip, and shoulder though were positioned 50, 70, and 90 mm in front of the back foot, respectively. Provincial level batters have also been shown to position their head significantly further forward of their centre of mass, with the majority of the mass concentrated over the front foot (see Taliep et al., 2007). This body orientation also causes the front shoulder to be placed 80 mm in front of the left toe (see Stretch et al., 1998). This stance has been implicated with the ‘forward press’, by which the batter moves (presses) forward in anticipation of a fuller-length delivery which will bounce close to the batter, given that fuller-length deliveries are the most commonly occurring deliveries, and generally present the greatest threat of dismissal for the batter. This initial movement tends to occur irrespective of where the ball will bounce; the batter can transfer weight onto the back foot following the short quick step forward when the ball is pitched further away from the batter (see Thomlinson, 2009). It was also found that the batters examined by Stretch et al. (1998) preferred to adopt a wider stance than that recommended by the coaching literature (460 vs. 100–350 mm; Marylebone Cricket Club, 1987), most likely as a means of promoting a lower centre of gravity to permit a stable head position and distinct view of the approaching bowler.

An interesting contrast between coaching and scientific literature lies in the side-on nature of the batting stance. Batters are typically coached to stand very side-on to the approach of the bowler, yet highly skilled batters have been shown to adopt a relatively open stance, exhibiting a moderate degree of rotation of the front shoulder in the transverse plane (mean = 26° Stuelcken et al., 2005). It has been proposed that this degree of openness may allow the batter to observe the bowler and ball with both eyes, without requiring either a large degree of head rotation, or simply observing the bowler with just one eye. An interesting yet scientifically unexplored area is whether the dominant eye of the batter influences the stance (and subsequent movements) of the batter. Animals with binocular vision tend to have one dominant eye which is used in tasks of alignment (e.g. as is evident in darts and snooker, and is likely to occur in hitting tasks). Golfers are also encouraged to allow their dominant eye to determine their stance whilst putting: with those who are 'cross-dominant' (whereby the dominant eye is opposite to the dominant hand) to adopt a squared side-on stance; and those who are 'same-side dominant' (whereby the dominant eye is on the same side as the dominant hand) are encouraged to adopt a slightly open stance (see Farnsworth, 2009). Although studies examining the interaction between eye dominance and handedness have provided contradictory findings, much of the evidence suggests that there is no relationship between eye and hand dominance resulting in successful batting performance (for more detailed information, see Adams, 1965; Laby et al., 1998; Erickson, 2007). However, anecdotally it is often suggested, in line with the recommendations of Farnsworth (2009), that it may be advantageous for a right-handed batter to have a dominant left eye as it has the clearest unobstructed view of the oncoming bowler and ball. If a right-handed batter were to have a dominant right-eye, there is greater reason for the batter to have a more rotated stance. A simple kinematic comparison may help to ascertain whether the stance and subsequent movements of batters are influenced by their ocular dominance.

*Backlift and preparatory movements*. Examinations of the backlift of the bat provide an interesting insight into how skilled batters achieve control of the effector (i.e. the bat) to effectively and efficiently swing their arms to successfully strike an approaching ball. Many batters have been observed to adopt a backlift that is skewed away from their body, rather than positioning their bat directly behind them as is commonly advocated by the coaching literature (e.g. Marylebone Cricket Club, 1987), and contrary to what logically may be expected to be the most efficient means of preparing for a straight and efficient downswing. Taliep et al. (2007) found that the angling of backswing away from the body was common, and was similar across skilled and lesser-skilled batters (26°and 27°, respectively, in relation to the stumps). It has been proposed that this angle may provide a comfortable position for the batters to place their hands in preparation for the subsequent downswing, and may allow for a more 'rotary' movement of the wrists by which the bat backswing and downswing can be performed in a continuous motion, rather than in two distinctive phases. Further examinations are needed to determine *how* the backlift angle may influence the path of the bat during downswing prior to making bat–ball contact. Concurrent analyses of kinematics, EMG, and inertial sensors may aid in determining how the angle of backswing influences the bat speed in downswing, muscle recruitment in the forearm and wrists, and the resultant forces imparted on the ball.

Stuelcken et al. (2005) have proposed that batters manoeuvre their bat using their wrists as a lever to position the bat close to the body's centre of mass; this may help to keep the centre of mass of the bat close to the batter's base of support, and ultimately to allow a later downswing, helping to overcome the temporal constraints inherent in batting. If the wrists were to be moved away from the body in the backswing of the bat, more energy and more time would be required to produce the backswing and downswing. If the wrists are kept close to the body, the batter is afforded a mechanical advantage as the moment of inertia required to move the bat at a given bat velocity is reduced; this decreases the amount of muscular effort required to play a stroke, and the bat can travel through a smaller swing arc to enable faster movements of the bat. If the downswing of the bat can be initiated at a later moment in time, the batter is afforded a temporal advantage as he or she is able to observe additional ball-flight prior to initiating the downswing to hit the ball.

As the bat is lifted backwards to the top of the backlift, other movements are produced to place the batter in the best possible position from which to forcefully swing at the ball.

In preparation for bat–ball contact, it has been proposed that the batter's front shoulder moves downwards and towards the direction of the bowler, reflecting the batter's intention to transfer weight onto the front foot in anticipation of a fuller-length delivery (Stuelcken et al., 2005). The depression in the front shoulder enables the head to be positioned in front of the body's centre of mass to maintain the weight distribution on the front foot in accordance with the forward press adopted by batters during their stance (Taliep et al., 2007). Changes in hip and shoulder angle observed from stance through to the completion of the backlift have been interpreted as the batter maintaining their intention to transfer weight onto the front foot (Stuelcken et al., 2005). This may also help to exploit the physiological properties of the musculo-tendonous complex, as rotation of the hips and shoulders is used to generate optimal force to take advantage of the stretch-shortening cycle (e.g. Bobbert et al., 1996; Burden et al., 1998; Hamill & Knutzen, 2003). Additionally, kinetic findings by Stretch (1993) and Stretch et al. (1995, 1998) suggest that during the backlift, the top hand plays the dominant role in maintaining control of the bat, with only reinforcement from the bottom hand. Further attention is required to determine whether and how the backlift is modified according to the forcefulness of the stroke; for example, key differences in the backlift angle and speed may be evident between attacking and defensive strokes.

The most appropriate time to initiate the backswing is a key issue for players and coaches: most coaching literature suggests that the backlift should be initiated as the bowler prepares to release the ball (e.g. Tyson, 1994; Australian Cricket Board, 2000), though an alternate school of thought suggests that the bat should be lifted earlier, and left in the air to remove the need for a later backlift. A number of elite batters have adopted this newer modified backlift in an attempt to simplify the batting technique, supposedly to help in minimising the temporal constraints required when initiating a later backswing. Although this modified technique may have received support from some coaches and athletes, from a scientific standpoint, there may be two specific kinetic limitations that are worthy of further consideration. First, it is possible that the backswing of the bat is used to counter-balance the torque about the centre of mass produced by the forward movement of the front foot. Second, the backswing generates kinetic energy in the arm muscles based on the stretch-shortening cycle which can be used to generate a more forceful downswing; however, this energy will dissipate if the bat is held up in the air for an extended period of time. A comprehensive examination of EMG and bat forces is warranted to establish the most efficient means of backswing to support forceful swings of the bat.

Preparatory movements (or *trigger* movements) are commonly performed by batters moving their feet prior to the bowler releasing the ball. It has been proposed that preparatory movements provide batters with a batting 'rhythm', enabling batters to organise and prime their foot movements in preparation for ball release (Woolmer, 1993). It is also thought that by establishing a rhythm, batters may be more accurate in the timing of their foot movements to place themselves in a most appropriate position from which to play their shot. In one study examining preliminary movements, the most common movement was for batters to move their back foot backwards and across in front of the stumps, following common coaching advice to protect the stumps behind them (Stuelcken et al., 2005). This preparatory movement may actually be advantageous in helping to overcome the temporal constraints of batting by reducing the visual-motor delay. Lee et al. (1983) have argued that it is quicker and easier to modify a movement that is already in progress, rather than when initiating movement from a stationary position.

Thomlinson (2009) interpreted force-plate data in batting to suggest that batters prior to the initiation of a definite front-foot movement tended to move their centre of mass backwards (away from the bowler) just prior to the moment of ball release, generating an increased ground reaction force under the batter's back foot. This force is then used to initiate the early definitive stride forward shown immediately after ball release. Similar behaviour has also been observed in baseball where batters shift their centre of mass backwards prior to the initiation of the forward stride in an act of loading to initiate the kinetic link (see Welch et al., 1995). Stuelcken et al. (2005) supported this finding as they found that the centre of mass of cricket batters shifted 70 mm forwards just 0.08 s prior to impact, suggesting the batter's intention to transfer momentum into the stroke. Despite there being very limited knowledge in either the coaching or scientific literature addressing the necessity of preparatory movements, many coaches advocate that a trigger movement complicates what should be a simple process for the batter to simply see the ball and move appropriately. Furthermore, it is highly desirable to possess a stable head to obtain the most accurate information about ball-flight information. When the head is moving, the batter must account for the head and ball movement to be in the right place at the required time. It is conceivable that trigger movements adversely affect the ability of the batter to maintain a stable head position, particularly at the moment of ball release when key ball-flight information must be observed as acutely as possible. Scientific work examining the impact of trigger movements on head position, on foot movements, and ultimately on the quality of bat–ball contact are desirable.

*Initiation of front-foot movement and downswing of the bat*. Successful batting in cricket involves performing decisive and appropriate foot movements that enable optimal positioning from which a stable foundation can be generated to successfully strike the ball (Bradman, 1958; Tyson, 1994; Cricket Australia, 2005). When analysing front-foot strokeplay (i.e. the drive and defensive shot) against a full-length delivery, it was observed that stride length was shorter when performing the drive than that when performing a defensive stroke; however, initiation of front-foot movement occurred later whilst performing the drive (see Stretch et al., 1998). It is proposed that this later foot movement coalesced with the shorter stride-length to form a better fulcrum from which to transfer the batter's centre of mass into the stroke. This transfer of momentum is achieved through the flexion of the front knee and raising the heel of the back foot, serving to stabilise the lower body. An additional feature of skilled batting was a forward and downward displacement of the head immediately prior to the moment of bat–ball contact to ensure that the batter's momentum continued through the stroke, and prevents the batter from raising their centre of mass which can result in the ball being struck in the air, increasing the likelihood of the ball being caught by an opposing fielder (Tyson, 1994; Stretch et al., 1998; Taliep et al., 2007).

In an examination of 10 highly skilled cricket batters, Thomlinson (2009) demonstrated that nine of the ten batters initiated a forward movement immediately following ball release, irrespective of the bounce point or shot type. This finding is in direct contrast to the existing coaching philosophy in which batters are advised to move forward to a full-length delivery, or to move immediately backwards to a short length delivery, and may reflect an 'evolution' in batting by which modern batters seek to press forward in expectation of the fuller-length ball. Thomlinson found that, although the forward movement was initiated at approximately the same moment for all trials, the length of the stride forward was modified according to the distance from the batter that the ball-bounced. When the ball was full (bouncing close to the batter), the batter produced a large step forward in an attempt to hit the ball immediately after it bounced. When the ball was short (bouncing well before the batter), the forward stride was cut short so that the batter could push backwards to hit the ball a longer time after bouncing, allowing for appropriate adjustments to be made in the case of lateral deviations in ball-flight. Thomlinson interpreted that these foot movements were fixed (i.e. inalterable) following movement initiation, and as the foot movement was initiated immediately following ball release, after allowing for the visual-motor delay, it was suggested that batters were capable of predicting ball-length prior to ball release. Alternately, it seems more feasible that batters are capable of modifying their foot movement following movement initiation, that is to say, that they are capable of performing online alterations to modify the length of the stride following movement initiation. Studies on baseball batting have shown that batters initiate their step forward based on the movement kinematics of the pitcher. In their study, Hubbard and Seng (1954) observed that baseball batters coupled the initiation of their step forward with the release of the ball from the pitcher, while the duration of the step and the initiation of bat-swing varied based on ball's speed. More recently, studies comparing the kinematics of the pitcher throwing a fastball and a change-up observed that step initiation of the batters was earlier for a change-up and later for a fastball; however, the duration of the step was longer for the change-up (see Ranganathan & Carlton, 2007). This finding supports the utilisation of a prospective strategy by the batter to make online alterations to movements prior to interception, based on the identification and interpretation of kinematic movement variations of the pitcher and subsequent ball-flight.

Very few biomechanical studies of cricket batting have found defining characteristics which differentiate skilled from lesser-skilled batters. One exception lies in the strength of the coupling between the planting of the front foot and the initiation of bat downswing in a forward drive. In a cross-sectional examination of batters of different developmental and skill levels, Weissensteiner (2008) observed that batters of greater skill were more likely to initiate the downswing of the bat at the exact moment that the front foot was planted on the ground. Players of lesser skill were found to be less likely to link these two events. These findings provide a potential basis for tracking the development of skill in batting, yet little is known about why this relationship may be important. A good balanced downswing is likely to rely on the creation of a strong, stable base of support, and this tight coupling may be a demonstration of most efficient timing with the downswing occurring immediately following the establishment of this base of support. The findings do provide an indication for a strong coordination of the upper and lower body in hitting; however, further work is required to examine whether this kinematic relationship exists for a variety of different types of shots, and whether this coupling is a skill which is a necessary requirement in the development of expertise. Skilled batters also demonstrated greater variability in backlift time than downswing time (22.0% vs. 12.6%, respectively), a finding which bears resemblance to the findings of Bootsma and van Wieringen (1990), which demonstrated a decrease in variability in the bat-swing from swing initiation to bat–ball contact. It is thus proposed that the relatively greater variability among skilled batters in backlift time is due to the fine-tuning of movement based on the ability of skilled batters to identify and interpret advance information relatively earlier than lesser-skilled batters. The reduction in the variability of downswing suggests that skilled batters may have already adjusted accordingly to the type of delivery and require only minute adjustments to ensure successful interception – providing further evidence for a prospective control of bat-swing (for more information, see Burgess-Limerick et al., 1991).

Traditionally, the downswing of the bat is believed to begin immediately following the backlift (i.e. it follows a continuous motion), with path tracings of the bat showing a distinctive loop linking the two events (e.g. Stretch et al., 1998; Stuelcken et al., 2005). In addition to the lever action adopted by batters in their backlift (Stuelcken et al., 2005), this continuous motion promotes faster movements of the bat and as a result allows batters to shorten the downswing-to-impact time and facilitates the use of additional ball-flight information prior to the initiation of bat downswing (e.g. Abernethy, 1981; Abernethy & Russell, 1984; Bootsma & van Wieringen, 1990). Furthermore, the body orientation developed during the backlift phase exploits the stretch-shortening cycle and can immediately transfer the summation of those forces into the stroke for more forceful hitting.

*Execution of the stroke*. Bat-speed is an important element of batting when seeking to hit a ball as hard as possible; however, the requirement to hit the ball away from 11 fielders produces a unique constraint for batters to contend with as the ball is hit. At the moment of bat–ball contact, skilled batters have been shown to angle their bat downwards to ensure that the ball is hit into the ground, minimising the likelihood that the ball will be caught by a fielder (see Stuelcken et al., 2005). Skilled batters were found to position their head further forward than lesser-skilled batters (304 mm vs. 193 mm), enabling them an advantage in the transfer of momentum into the stroke (Taliep et al., 2007). Whilst performing a drive in a game environment, peak bat velocities of batters were observed 0.02 s prior to impact (see Stuelcken et al., 2005), generated through the pendulum movements of the shoulder, elbow, and wrists (Stretch et al., 1998; Taliep et al., 2007). However, cricket batting demonstrates lower bat velocities than other striking tasks such as baseball and tennis (see Elliott et al., 1989; Marino, 1989; Stuelcken et al., 2005). This result is most likely due to the unique demands of the task affecting the speed-accuracy trade off – successful cricket batting may, at times, necessitate sacrificing the speed of movement to enhance the accuracy of the stroke. Additionally, the ability to generate large swing velocities is dependent on the direction of the swing (e.g. tennis forehand vs. cricket batting drive) and also the inertial characteristics required to initiate the swing of a heavy wooden cricket bat when compared to a lighter graphite tennis racquet.

The regulation of grip forces during the execution of a stroke provides an interesting examination of motor control when comparing movement which seek to *receive* or *produce* a collision. Turrell et al. (1999) and Li and Turrell, (2002) proposed that when receiving a collision – as would occur when playing a defensive stroke – the changes in grip forces are minimal prior to bat–ball contact, whereas large changes occur post-impact due to a latency reflex to prevent the bat from slipping from the hand. When producing a collision – as occurs when performing an attacking stroke – peak grip forces were observed at impact to ensure forces are transferred to the ball. These findings are similar to those observed in golf (e.g. Shibayama & Ebashi, 1983) and baseball (e.g. McIntyre & Pfautsch, 1982), and support the findings of Stretch (1993) in cricket who found that peak forces occurred after impact (0.06 s) when performing a defensive stroke, whereas peak forces were observed immediately *prior* to impact (0.02 s) when performing a drive.

*Follow-through*. The follow-through of the bat-swing, which takes place following the moment of bat–ball contact, helps to ensure that the impulse generated by the swing of the bat is transferred to the ball, while ensuring that sufficient time is available for the body segments to decelerate (Stretch et al., 1998). The head position of skilled batters enables the transfer of momentum to continue through the stroke and to distribute weight onto the front foot to maintain balance. On the other hand, lesser-skilled batters are less able to generate sufficient momentum to distribute their weight appropriately onto the front foot whilst performing the stroke, providing a key reason for their lesser ability to maintain balance following bat–ball contact (Taliep et al., 2007). Most batters prefer to deviate from the traditional 'full' follow-through of the bat, where the bat finishes over the front shoulder; rather they tend to adopt an abbreviated follow-through which requires a faster dissipation of energy, but is typically performed in a manner which does not negatively impact force production at bat–ball contact (Stretch et al., 1998; Stuelcken et al., 2005). This abbreviated follow-through has been implicated with higher rates of arm injury, particularly in the front elbow, as the increased torque required may lead to the onset of repetitive strain injuries such as lateral epicondylosis (tennis elbow). Future examinations and modelling using EMG of the arm musculature may help to identify and develop appropriate injury prevention strategies.

## Summary

Cricket batting is an incredibly complex motor task which requires the batter to overcome, at times, highly excessive spatial and temporal constraints to effectively and successfully hit the ball. The biomechanical literature has provided a series of studies which have at times advocated, and at other times questioned, the prevailing coaching philosophies developed over many years. These results in themselves though may fall short of being used in the most effective manner if they are not used to effectively inform, challenge, and change coaching practices without the use of sound theories of teaching and learning. The emerging literature examining skill development and visual-motor control is useful in both informing and interpreting the biomechanical literature on hitting skills. This multidisciplinary approach highlights the interdependency between two disparate scientific fields and should encourage scientists to embrace the findings from distinctive fields to inform and enlighten our knowledge of the underlying processes involved in successful hitting. It is proposed that as scientific examinations evolve to further our understanding on how athletes are capable of hitting a ball, some of the most useful contributions will be from those studies which seek to combine theories of visual-motor control with best practice biomechanical analyses.

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