NEXT GENERATION CRICKET BOWLING MACHINE

By

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Abstract

Cricket is a traditional team sport played in over 100 countries around the world. Unlike many mainstream sports, cricket has seen little research and development within the equipment used to play the game. Ball launching machines have been used as a training aid in a number of sports including cricket, however, as with the playing equipment used, these too have seen little development. Current cricket bowling machines enable players to train at a high intensity producing repeatable deliveries for batsmen to hone their skills. A need has been established by the coaching staff of the England and Wales Cricket Board (ECB) for a cricket training system that provides batsmen with a match realistic environment in which to train. Existing cricket bowling machines do not offer batsmen pre-release visual information that they would receive in a match situation and the most popular models release moulded, dimpled balls that do not replicate the performance of cricket balls.

The research within this thesis focuses upon the development of a novel cricket bowling machine and establishes the performance criteria for bowling machines aiming to replicate elite human performance. A bowling machine has been developed to impart cricket balls with flight characteristics measured from elite performance. Of particular focus has been to impart correctly oriented spin onto cricket balls, a feature that is not available on current models and necessary to accurately replicate elite spin bowling in particular. The bowling machine has undergone a series of design alterations during the undertaken research. At each stage the performance of the machine has been evaluated against elite human performance measured during player testing and elite match play analysis. Results show that the machine is capable of outputting deliveries with ball flight characteristics akin to those bowled by elite athletes.

Additional work has been carried out to analyse the differences in the timing of movements made by a batsman when facing a human bowler and a bowling machine. A case study was conducted within a training environment comparing the movements made by a batsman with the visual information he received in the two scenarios. The conclusions drawn from the study are that against bowling machines the batsman anticipates each delivery earlier and moves his feet later than when facing a human bowler.

A second case study is presented portraying the development of a tactile method to define the orientation of a cricket ball seam. Cricket bowlers release the ball in a specific orientation depending on the delivery type they are releasing. It is therefore imperative to maintain control over the orientation of the ball prior to machine input if the ball is to be output correctly.

Publications Arising From This Work

Cork, A. West, A. Justham, L. *High Speed Video Evaluation of a Leg Spin Cricket Bowler.* The Impact of Technology on Sport II, 2007.

Cork, A. Justham, L. West, A. (2008) *Cricket Batting Stroke Timing of a Batsman When Facing a Bowler and a Bowling Machine.* The Engineering of Sport 7, Volume 1, 143-150.

Justham, L. West, A. Cork, A. (2008) *Quantification and characterisation of cricket bowling technique for the development of the parameters required for a novel training system for cricket.* Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology, Volume 222, Number 2/2008, 61-76.

Cork, A. Justham, L. West, A. (Under Review) *Comparative Study of Performance During Match Play of Elite Level Spin and Pace Bowlers in Cricket.* Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology

Cork, A. Justhám, L. West, A. (Under Review) *Three-Dimensional Vision Analysis to Measure the Release Characteristics of Elite Bowlers in Cricket.* Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology

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1: Introduction

1.1: Research Motivations

Modern day sports coaching often utilises ball launching machines as a means of providing players with repetitive situations and the ability to train at a high intensity. Ball launching machines are used in the training of a number of sports, notably baseball, tennis and cricket. Cricket bowling machines are commonly used in net training sessions when batsmen train alone or to reduce the workload of a team's bowlers.

The increased revenue in sports such as baseball has seen the technological advancement of pitching machines where programmable sequences of pitches and visualisation screens have been incorporated into training systems. Cricket is a popular sport played in more than 100 countries, however it has not received the financial input seen in baseball. As a result, research and technology conducted within cricket and particularly cricket bowling machines has remained limited. Unlike baseball, where the ball is launched through the air at the batsmen, cricket requires the ball to bounce on the pitch and the behaviour of the ball post bounce plays a vital role in the outcome of the duel between batsman and bowler. When throwing a baseball, the pitcher must use the aerodynamic properties of the baseball to his advantage if he is to beat the batter. In cricket the bowler must not only control the aerodynamics, but he must also predict the level of interaction between ball and pitch and manipulate the ball to achieve the desired bounce and deviation. The design of the cricket ball, comprising a multi-layer construction with a leather outer and a protruding stitched seam about its equator enables bowlers to create a wide range of deliveries that behave differently through the air and post contact with the pitch. Cricket bowling techniques vary considerably, from the length of bowlers' run ups to the speed of arm rotation, each action is unique and results in a plethora of ball flight characteristics (ball release speed, spin rate, etc) seen throughout all levels of the game.

In 2003, the staff of the England and Wales Cricket Board (ECB) recognised a need for the development of a cricket training system that would provide batsmen with a match realistic environment in which to train. The work conducted by Laura Justham (2003 - 2007) resulted in a laboratory prototype cricket bowling machine produced at Loughborough University. The work conducted within this thesis commenced in 2005 and is a continuation of the research initiated by Justham developing the design of the prototype bowling machine and formalising a greater understanding of the performance criteria of a cricket bowling machine.

1.2: Research Objectives

The research carried out within this thesis has been focussed upon identifying the performance requirements of a cricket bowling machine commissioned to recreate realistic and repeatable bowling deliveries. A research question has been developed based upon this focus and four research objectives were identified. The research question states:

"The outcome of this research should include the design and manufacture of a prototype cricket bowling machine which is able to impart spin and speed onto a cricket ball representative of elite human performance in a controlled and reproducible manner. The research should include the identification of machine performance criteria for recognised delivery variations and any additional functionality which is desirable for a cricket training environment."

The research question has resulted in the identification of four objectives:

(1): The identification of a set of performance criteria essential for a cricket training system, with particular emphasis upon the bowling machine.

(2): The development of elite training programmes.
(3): The design, manufacture and testing of a novel cricket bowling machine.
(4): The identification of further requirements which are desirable within a cricket training environment.

It was anticipated that the recreation of human bowling deliveries would form a significant part of the research. The identification of common delivery variations would be required with measurements taken to establish the typical differences in ball flight characteristics for each variation. It was hypothesised that deliveries released by wrist spin bowlers would see the greatest level of variation and that due to the high level of disparity between bowlers' actions, ball flight characteristics could be unique to each bowler. It was anticipated that the machine was unlikely to perform with 100% efficiency, however, the target for bowling machine performance was established as less variability than seen in elite performers under match conditions.

The first of the objectives was the identification of the performance criteria of a training system, specifically the bowling machine within the system. If a training system is to provide a batsman with a match realistic environment in which to train, it is imperative that the deliveries output by the machine have the same ball flight characteristics as those released by human bowlers. The common delivery variations have been reviewed using existing literature from research publications and coaching manuals and a series of player tests were conducted where the ball flight characteristics of bowler's stock deliveries and variations were evaluated using synchronised, orthogonal high-speed video cameras. The launch characteristics of deliveries have been evaluated along with the pitching consistency of the bowlers.

The second objective was to develop programmes of deliveries for elite training. One of the recent requirements of bowling machines has been to emulate particular bowlers. This was specifically seen when England asked to use Merlyn, a spin bowling machine prior to the 2005 Ashes series in preparation for facing Shane Warne, the Australian wrist spin bowler. Analysis of elite bowling performance under match conditions was undertaken such that a series of deliveries could be programmed into a machine allowing batsmen to train against deliveries representative of those released by a particular bowler.

The third objective which was addressed was the design, manufacture and testing of a novel prototype cricket bowling machine design. This work has formed the core of the research carried out. The performance of elite bowlers measured during player testing and elite match play analysis has created the basis for system validation. Testing has been carried out within a laboratory environment and at the ECB National Cricket Centre, a state of the art indoor facility.

The fourth objective of the research was the identification of additional system requirements that are necessary for a cricket training environment. There have been two case studies carried out. The first focuses upon the differences in the movement patterns of a batsman when facing a human bowler and a bowling machine. A review of existing literature on the necessary information a batsman requires in order to judge an oncoming delivery has been undertaken along with a testing session conducted within a training environment. The second case study describes the development of a method to determine the orientation of a cricket ball. Delivery variations often see bowlers changing the orientation of the ball in their grip. It is therefore important for a bowling machine to replicate this and release balls in the correct orientation. A number of potential methods are reviewed and one pursued using a tactile method to define the position of the seam.

1.3: Thesis Structure

This thesis has been divided into eight Chapters and two Appendices based upon the objectives outlined within the research question. Each Appendix corresponds to a Chapter within the main text of the thesis. The areas of new knowledge have been developed throughout the project based upon the research objectives. The structure of this thesis and the new knowledge gained from each Chapter is reviewed in Figure1.3.1:

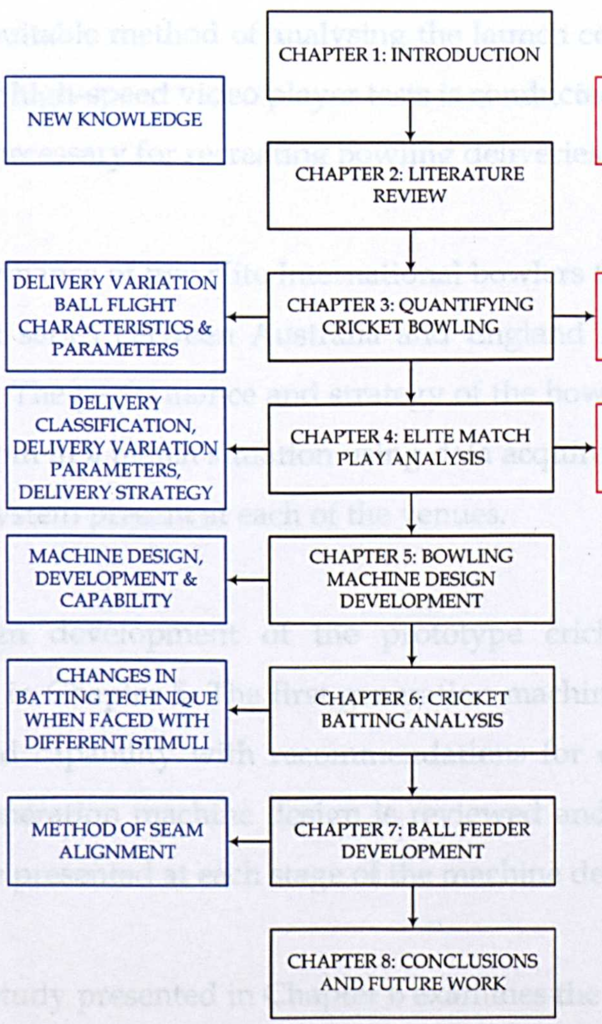


Figure 1.3.1: The thesis structure and the new knowledge developed from the work reviewed in each Chapter.

The literature reviewed in Chapter 2 begins with an overview of the game of cricket and the most important piece of cricketing equipment for the work undertaken, the ball. A review of cricket bowling is conducted with a focus upon the common delivery variations and the techniques observed. The aerodynamics of the cricket ball and its effect on ball flight is considered along with the demands placed upon batsmen when facing deliveries. Current cricket bowling machine designs are assessed and the role they play in cricket coaching is examined.

The research presented in Chapter 3 is concerned with quantifying the ball flight characteristics of deliveries and variations bowled by elite cricketers. A number of analytical systems are reviewed with conclusions drawn regarding the most suitable method of analysing the launch conditions of a cricket ball. A series of high-speed video player tests is conducted to quantify the required variables necessary for recreating bowling deliveries.

The performance of two elite International bowlers throughout the five match Ashes test series between Australia and England in 2006/07 is detailed in Chapter 4. The performance and strategy of the bowlers is analysed, one pace and one spin in a match situation using data acquired from the HawkEye ball tracking system present at each of the venues.

The design development of the prototype cricket bowling machine is presented in Chapter 5. The first generation machine is reviewed in terms of design and capability with recommendations for development drawn. The second generation machine design is reviewed and the results of validation testing are presented at each stage of the machine development.

The case study presented in Chapter 6 examines the changes in movements of a batsman when facing a cricket bowling machine and a human bowler. A synchronised, multi high-speed camera setup allowed for the analysis of the timing of a batsman's movements with respect to the visual information available to him. Initial conclusions are drawn from the trial regarding the critical information that needs to be provided to batsmen in order that they judge an oncoming delivery.

The development of a ball feeding mechanism is described in Chapter 7 with initial testing of a ball orientation device conducted. If a training system is to allow batsmen to train alone, the system must automatically input balls into the machine in the correct orientation. The ball orientation device tested is capable of analysing a ball and defining the axis of the seam.

A discussion of how the research conducted within this thesis has contributed to new knowledge and the recommendations for future work is presented in Chapter 8.

2: Literature Review

The purpose of this chapter is to review the background research conducted into the game of cricket, cricket bowling and the variations of deliveries seen. In addition, the demands placed upon the batsman when faced with an oncoming delivery will be reviewed along with current ball launching technology and its use within sports coaching. The following research questions are addressed in this chapter:

- How are delivery variations categorised?
- How do bowlers grip the ball and does this change for delivery variations?
- What research has been conducted to quantify the ball flight characteristics of deliveries?
- What strategies are employed by bowlers when selecting deliveries to bowl?
- What techniques are used by bowlers to impart spin onto the cricket ball?
- How does aerodynamics affect the flight of a cricket ball?
- What information do batsmen require in order to judge an oncoming delivery?
- From where do batsmen obtain information to judge an oncoming delivery?
- What are the design variations seen in currently available ball launching devices?

2.1: The Game of Cricket:

Cricket is a sport played between two teams of eleven players on a circular grass field, in the centre of which is a flat strip of short grass 20.12 metres long and 2.64 metres wide (see figure 2.1.1). At the centre of either end of this strip three wooden stumps are placed in a straight line, these stumps support two wooden bails that rest in grooves on top. The combination of stumps and bails forms the wicket, the height of which is 0.72 metres.

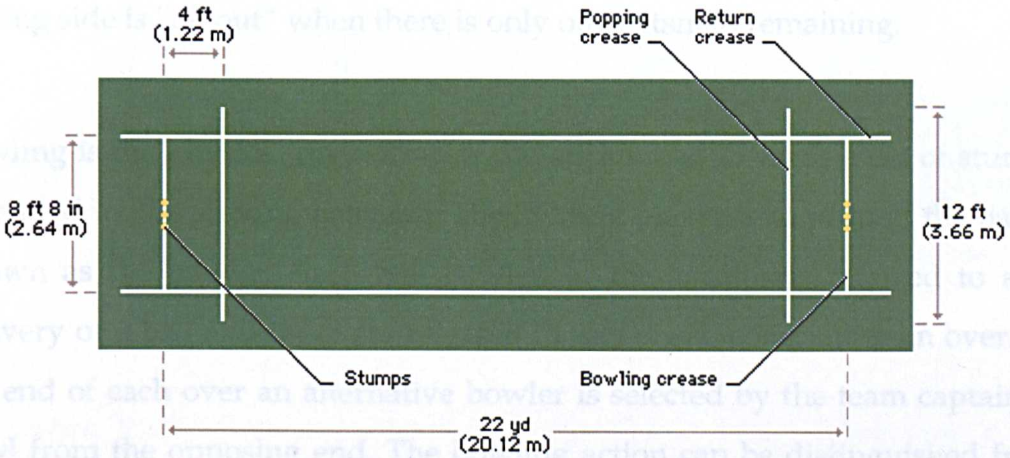


Figure 2.1.1: The dimensions of the central strip of a cricket pitch (Encarta, 2008)

There are two disciplines undertaken by each team, batting and fielding. Over the course of a match both sides will bat and both sides will field. The primary objective for the batting team is to score as many runs as possible while the fielding team endeavour to reduce the number of runs scored and get the batsmen "out".

The batting team is represented by a pair of batsmen who are present on the pitch at one time. The batsmen use a wooden bat to strike the cricket ball which has been propelled towards the wicket they are defending. Runs are scored when the batsmen cross and reach the popping crease at the opposite end of the pitch after the ball has been hit or anytime while the ball is in play (MCC, 2008). The decision to attempt a run is ideally made by the batsman who has the better view of the ball's progress and the decision is communicated through calling to the other batsmen. Running is a calculated risk because if a fielder breaks the wicket with the ball while no part of the batsman or his bat is grounded behind the popping crease the batsman nearest the broken wicket is run out. Runs can also be scored if the batsmen hits the ball over the boundary rope along the perimeter of the playing field. The fielding side try to dismiss the batsmen by various methods until the batting side is "all out" when there is only one batsman remaining.

Bowling is the physical propelling of the cricket ball towards a set of stumps defended by the striking batsman. The fielding player who propels the ball is known as the bowler. Each ball bowled at the stumps is referred to as a delivery or a ball and these are released in sets of six, completing an over. At the end of each over an alternative bowler is selected by the team captain to bowl from the opposing end. The bowling action can be distinguished from throwing as the bowler must release the ball using a straight arm (extensions or hyperextensions of up to 15 degrees are permitted) otherwise the delivery can be deemed a "no ball" resulting in one run being added to the batting side's total and one extra delivery is required in order to complete the over.

2.2: The Cricket Ball:

Cricket balls are produced using a pre moulded cork core that is layered with wool yarn. The wool is wound when wet and under tension to compress each of the layers of cork. As the wool dries out it compresses the cork layers. Typically five layers of cork and six of wool yarn are used to create the core (Jarratt, 2001). This compressed core is wrapped in a leather cover that consists of four equal segments or quarters. These quarters are stitched together into pairs, using stitching which is not visible from the outside of the ball. These are known as the quarter seams and are set at right angles to each other on either of the ball hemispheres. The two hemispheres of leather cover are joined with a visible primary seam that consists of six rows of stitching and is a raised feature on the ball (see figure 2.2.1).

Figure 2.2.1: The internal construction of a cricket ball (left) and the protruding seam of the cricket ball (right) (Eager, 2006).

Balls used in the first class game in England and Wales must pass a test regime set out in British Standard number BS 5933:1994. The latest version of the standard was published in 1995 and consists of a sequence of eight tests that determine various aspects of the ball such as seam height, hardness and wear resistance (BS 5933:1994). The cricket ball is also covered by law 5, set in the rules of the game by The MCC. Law 5 states that the ball's circumference must measure between 22.4 cm and 22.9 cm and the mass of the ball must fall between 155.9 grams and 163 grams (MCC, 2008). Balls are produced in two colours, red for test match and four day cricket and white for one day cricket. In order for balls to be used in first class cricket in the UK, they must pass both law 5 and the British Standard.

2.3: Cricket Bowling:

Within the game of cricket there are two distinct styles of bowling: pace and spin. It is generally observed that a bowler will specialise in one of these disciplines, of which it is easiest to differentiate between by measuring the release speed of the delivery. Spin bowlers will typically release the ball at slower speeds than pace bowlers due to the complexity of the action involved and to increase the likelihood of deviation post contact with the pitch. The techniques of both disciplines will be reviewed in sections 2.3.3 (pace) and 2.3.4 (spin).

2.3.1: Stages of the Cricket Bowling Delivery:

The bowling delivery can be broken down into a number of sections: (a) the run-up to the crease, (b) the leap into the pre-delivery stride, (c) the mid bound, (d) rear foot contact, (e) front foot contact, (f) the release of the ball and (g) the follow through (Bartlett et al, 1996) (see figure 2.1.3).

Figure 2.3.1: The seven sections of the bowling delivery

The first stage of the bowling delivery is the run up ((a) figure 2.3.1). During this stage the bowler will make a final decision on the delivery type he is going to bowl based upon factors including the team's position within the game, the weather and pitch conditions and the batsman he is bowling to (Philpott, 1995). It is typically during this stage that the bowler will position the ball within his grip. He may decide to conceal this information from the batsman if it provides him with cues pertaining to ball type.

The second stage is the leap into the pre delivery stride ((b) figure 2.3.1). Here the bowler seen in figure 2.3.1 initiates the transition from the front-on run up position to the side on release position. This is because the bowler releases the ball from a side on position (see figure 2.3.2 (b)). If the bowler released from a front on position, the leap would be shorter and would not include the rotation (Portus, 2001).

The third stage is the mid bound ((c) figure 2.3.1). The bowler is not in contact with the ground and, in the case of the bowler pictured in figure 2.3.1, he has undergone the transition from a front on position to side on.

The fourth stage of the delivery is the rear foot impact ((d) figure 2.3.1). In the case of the right handed bowler, this will usually be the right foot. For the side on release technique the rear foot will land parallel to the bowling crease (see figure 2.1.1). At this point the rotation of the bowling arm is initiated, at the start of the "coil."

The fifth stage of the bowling delivery is the front foot impact ((e) figure 2.3.1). This is the point where contact is made between the bowler's front foot (for right handed bowlers usually the left foot) and the ground prior to the ball being released. As the bowler's momentum carries him forward, the weight is transferred from the rear foot to the front foot and the front foot becomes the bowler's only point of contact with the ground.

The sixth stage is the release of the ball ((f) figure 2.3.1). This is the point at which the ball leaves the bowlers hand and is thus the last opportunity for the bowler to influence the flight of the delivery. Pace bowlers will typically release the ball with a flick of the wrist and fingers down the back of the ball imparting backspin. Spin bowlers will impart spin onto the ball through the rotation of the wrist and/or fingers on releasing the ball.

The seventh and final stage of the bowling delivery is the follow through ((g) figure 2.3.1). This is the continuation of motion by the bowler post ball release and usually consists of a few steps to regain balance. At this point the ball is in flight and the bowler no longer has an influence on the ball's trajectory. The ball is subjected to external influences caused by the airflow around the ball that can lead to deviation and drift in flight.

2.3.2: Bowling Biomechanics:

Good technique for a fast bowler will be a combination of balance, speed and power (Lillee and Brayshaw, 1977) and is the result of three recognised anatomical positions that a bowler will deliver the ball from: side on, front on and mixed position. The MCC encourage the side on position as the optimal technique (MCC, 1987). This is where the rear foot lands parallel to the bowling crease and the shoulders point in a straight line down the pitch (see figure 2.3.2 (b)). The front on position is recognisable by the feet and chest facing straight down the pitch towards the batsman (figure 2.3.2 (a)). The third position, the mixed position, is often adopted by bowlers that have received little coaching during the early stages of developing their bowling technique. In this position the back foot is placed parallel to the bowling crease and the chest is front on, facing down the pitch (figure 2.3.2 (c)) (Elliot and Khangure, 2002). The spine is twisted and hyper-extended at release and can be the cause of many injuries, due to the twisting of the core of the body (Bartlett, 2003).

Figure 2.3.2: The three recognised release positions: front on (a), side on (b) and mixed (c) (a - eurosport, 2008, b – sporting-heroes.net, 2006, c – thegoogly.com, 2007).

With high forces acting upon the body during the delivery stride there is a high potential for injuries to occur, particularly in the lower back of the fast bowler (Elliott, 2000). The incidence of cricket injuries has been reported in club cricket to be 2.6 injuries per 10,000 hours played (Weightman and Brown, 1975). However Orchard et al (2002) report that in Australian first class cricket, a low of 19.0 injuries per 10,000 hours played rising up to 38.5 injuries per 10,000 hours of play was seen for one day international cricketers. These data suggest that injuries are more likely to occur in those that play and train more often and at a higher intensity than occasional recreational players.

The rigours of bowling for prolonged periods put a great deal of strain on the body, particularly for express paced bowlers (i.e. bowlers delivering balls > 90 mph (~45 m/s))(Dennis et al, 2003). Typically these bowlers have to withstand approximately three times their body weight on every stride of the run up and approximately five times their body weight during the delivery stride (Foster, 1983). If poor technique is adopted then the risk of injury with such high forces acting upon the body is dramatically increased. Three common back injuries seen in cricket bowlers are disc degeneration, stress fractures of the vertebrae and a condition known as a spondylolysis defect (see Figure 2.3.3).

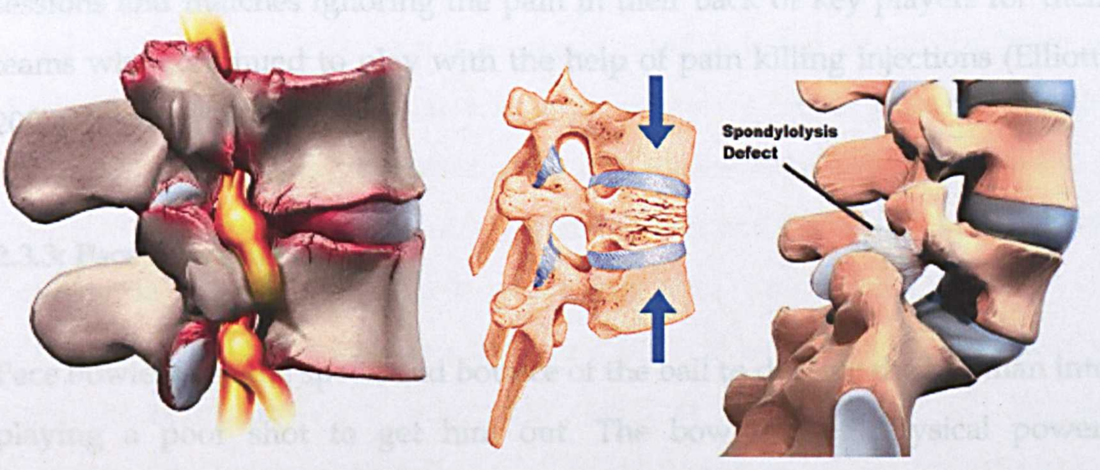


Figure 2.3.3: Three common injuries suffered by bowlers; disc degeneration (left), stress fracture of the vertebrae (centre) and spondylolysis (right) (MMG, 2006).

Disc degeneration occurs when there is continued overuse and the padded intervertebral discs between the vertebrae collapse leaving no cushioning between the vertebrae. Without the cushioning effect of the discs, the vertebrae in the spine are not able to absorb stresses, or provide the movement needed to bend and twist (Elliott, 2002).

Stress or compression fractures of the vertebrae occur in cricket when fast bowlers adopt a poor technique that involves twisting the body's core (i.e mixed action). The mixed bowling technique is often a cause of stress fractures due to the high levels of trunk extension during the bowling action (Stretch, 2003).

Spondylolysis refers to a defect in the vertebra of the lower back, particularly the last vertebra of the lumbar spine. The bony ring (pedicle) that protects the spinal nerves is the affected area. When a spondylolysis is present, the back part of the vertebra and the facet joints are not connected to the body - except by soft tissue. Most doctors believe that the spondylolysis is a stress fracture that has not been given the correct time to heal. The condition is commonly seen in bowlers who continued to bowl throughout the season in training sessions and matches ignoring the pain in their back or key players for their teams who continued to play with the help of pain killing injections (Elliott, 2000).

2.3.3: Pace Bowling:

Pace bowlers use the speed and bounce of the ball to deceive the batsman into playing a poor shot to get him out. The bowler uses physical power, technique and momentum to generate the speed of the delivery. The power aspect is created through physical training, technique is taught through coaching and momentum is built up during the bowlers' run-up (Lillee and Brayshaw 1977), which can measure up to 40 metres in length prior to the delivery stride in the case of some express paced bowlers (for example Pakistan's Shoaib Akhtar).

Abernethy (1981) classified bowlers by the speed at which they release the ball. The fastest bowlers (90+ mph) were classed as express pace, next came fast (80+ mph), then fast medium (60+ mph) and finally slow (40+ mph).

Slow paced bowlers will often try to use the aerodynamic properties of the cricket ball to their advantage and attempt to deviate the ball laterally from its path in the air during the delivery, utilising forces acting upon and around the ball's surface layer. This is referred to as swing (see section 2.4). Due to the pace of the delivery being less than express or fast bowlers, medium pace bowlers must maintain a high level of consistency and accuracy with their deliveries if they are to be effective. This is due to the increased time (i.e. Δt express to medium pace ≈ 200ms) a batsman will have to make decisions and react to a particular delivery, given the decreased speed of the ball. The medium paced bowler will often introduce variation into deliveries during an over. This can be done by changing the pace or pitching position of the delivery, swinging the ball, spinning or cutting the ball on release and often changes in the bowler's physical position when releasing the ball. Variation in length is more regularly seen in express paced bowling where the bouncer (i.e. typically pitching 12 metres in front of the batman's stumps) and the Yorker (typically pitching 1 metre in front of the batsman's stumps) deliveries are often used to claim batsmen's wickets (Lillee and Brayshaw 1977). When bowling at express pace the batsman has very little time (Δt = 439 ms (Abernethy, 1981)) to react to the oncoming delivery, however at slower speeds (i.e. approx 17.7m (Abernethy, 1981) at 55mph = Δt = 720 ms) the batsman has time to adjust and play a shot accordingly reducing the effectiveness.

For a standard delivery the bowler will hold the ball between the two first fingers and tip of the thumb with the seam vertical, aligned down the pitch (see figure 2.3.4(a)). On release the ball will rotate backwards as a result of the bowler "flicking" the ball out of the hand, this helps to stabilise the ball and keep the seam upright as it travels through the air (Wilkins, 1991).

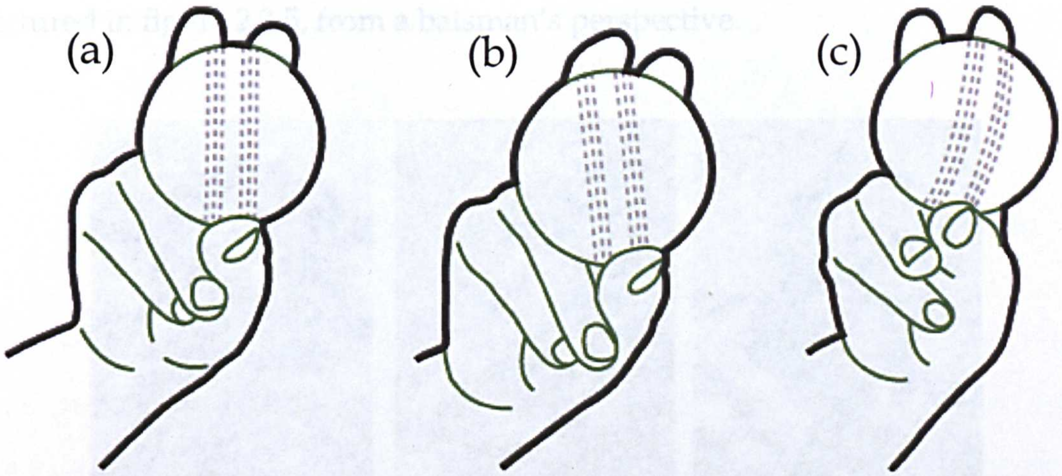


Figure 2.3.4: Three typical grips of a pace bowler as viewed from a batsman's perspective. The standard pace grip (a), the in swing grip (b) and the out swing grip (c) (BBC Sport, 2008).

For swing deliveries the bowler holds the ball with the seam vertical but aligned to either side of the wicket at approximately twenty degrees (Pont, 2006) from the direction of motion (see figures 2.3.4 (b) and (c)). The fielding team will polish one side of the ball while leaving the other side rough. This asymmetry combined with the angle of the seam causes the ball to deviate in the air by harnessing a pressure imbalance on either side of the ball resulting from the effect of the ball surface on the air flowing around it (see section 2.4).

Variation to the standard deliveries bowled by pace bowlers will often be found in the speed at which they release the ball. Bowlers with a high level of ability will often include a "slower ball" during their bowling spell. In order to be effective it is important that bowlers release the ball with as little change to the bowling action as possible. The idea of a slower ball is to trick the batsman into playing a shot too early such that he will either be caught or clean bowled (Willis, 1984). Methods of bowling slower balls vary between bowlers, Willis (1984) offers a number of alternative methods: releasing the ball from a yard further back than usual and slowing down the bowling arm are two such methods. However Willis believes that altering the grip is the easiest way of releasing a well concealed slower ball. Three such grips are pictured in figure 2.3.5, from a batsman's perspective.

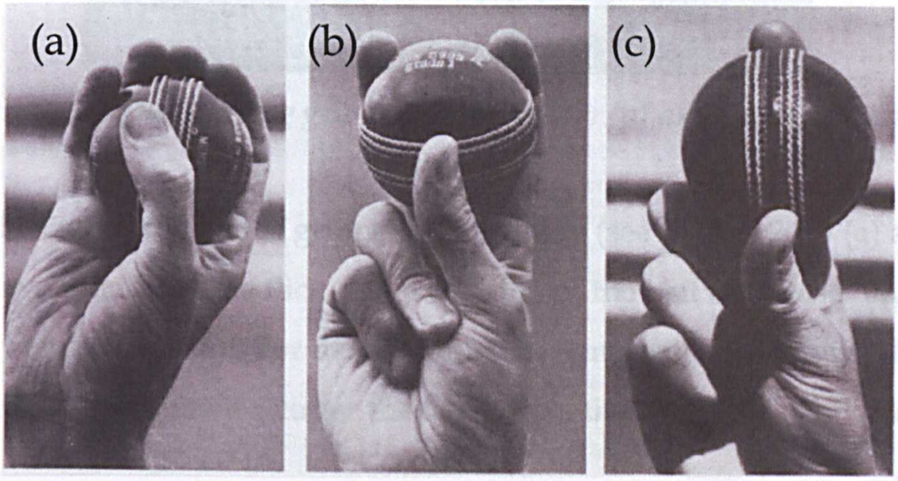


Figure 2.3.5: Three alternative grips used to bowl the "slower ball." Holding the ball deeper into the palm (a), placing the fingers across the seam (b) and gripping the ball with one finger (c) (Willis, 1984).

Pace bowlers will also release deliveries imparted with rifle spin (i.e. spin around the radial axis of the delivery (Wilkins, 1991) These deliveries are known as "cutters." These deliveries are bowled in two forms, the off cutter and the leg cutter. An off cutter will deviate towards a right handed batsman's leg side on pitching and a leg cutter will deviate towards a right handed batsman's off side. To bowl a cutter delivery, the bowler will grip the ball with the seam horizontal in the two finger and thumb grip previously seen for pace bowling (see (a) figure 2.3.4). For a cutter the two first fingers of the bowling hand will be offset, to the right of the seam for an off cutter and to the left for a leg cutter. The grip for each of these deliveries can be seen in figures 2.3.6 (a) and (b), from a batsman's perspective.

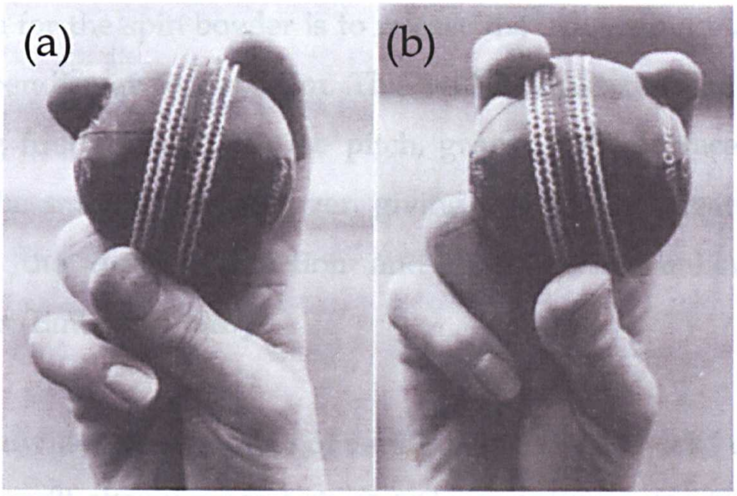


Figure 2.3.6: The bowling grip for the off cutter (a) and the leg cutter (b) (Willis, 1984).

To bowl a cutter, the ball is gripped accordingly (see figures 2.3.6 (a) and (b)) and the wrist and fingers flick down the side of the ball at release, imparting the rifle spin component. For the off cutter the hand will travel down the right side of the ball, for the leg cutter the left side of the ball (Lillee and Brayshaw 1977).

2.3.4: Spin Bowling:

Spin bowlers deliver the ball more slowly than pace bowlers (typically lower than 60 mph (see Chapters 3 and 4)). They release the ball from the hand in such a way that it imparts spin onto the ball. This is done by either flicking the ball with the fingers or rotating the wrist on release of the ball. There are two main types of spin bowler, referred to as finger spinners and wrist spinners. A right arm finger spinner's standard delivery will turn the ball towards the leg side of a right handed batsman on hitting the pitch (i.e. from left to right looking from the bowler's perspective). Conversely, a right arm wrist spinner will turn the ball away to the off side of a right handed batsman on hitting the pitch (i.e. from right to left).

The ball is held in the fingers of the hand, with the fingers generally placed across the seam to gain maximum traction on the seam (Illingworth, 1979).

One objective for the spin bowler is to release the ball with it spinning about the axis perpendicular to the seam. This will increase the likelihood of the seam making first contact with the pitch, gripping the surface of the pitch better than the smooth leather cover, giving the ball the greatest chance of deviating in the desired direction and often giving enhanced bounce characteristics (Emburey, 1989).

A spin bowler will have a number of variations on their "stock" delivery. This is where they will alter their technique to impart different spin orientations, speeds of delivery and trajectories. A top class spin bowler will be able to execute these variations with minimal visual change to their basic action in an attempt to deceive the batsman and draw him into a false shot (Philpott, 1995).

A batsman will have to study the spin bowler's movements and grip to determine any differences in the actions for each type of delivery. Often a batsman will also watch the ball as it leaves the hand to see which way the seam is spinning in order to make a shot selection. A tactic often employed by bowlers during the run up and bound is to conceal their grip on the ball and the orientation of the ball for as long as possible (see figure 2.3.7).

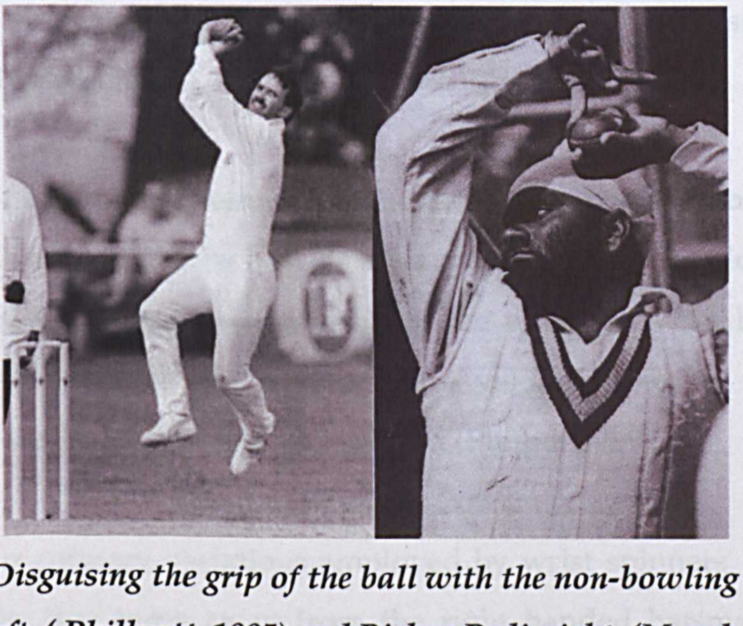


Figure 2.3.7: Disguising the grip of the ball with the non-bowling arm. Trevor Hohns, left, (Phillpott, 1995) and Bishen Bedi, right, (Murphy, 1982).

Delivery variations within a spin bowlers repertoire may include: (i) varying the point of release in the delivery stride, (ii) changing the pace of the ball through the air, (iii) varying the horizontal angle of the delivery by moving further or nearer to the stumps and (iv) altering the vertical angle of the delivery. Varying the vertical launch angle of deliveries is a common tactic used by spin bowlers who bowl flighted deliveries where the arc of the trajectory goes above the batsman's line of sight. This forces the batsman to alter his head position if he is to follow the ball in flight. These deliveries will generally be slower in pace than a stock delivery and pitch a little shorter with the intended result of a batsman playing a shot too early and being caught out (Illingworth, 1979).

2.3.4.1: The Wrist-Spin Bowler:

The stock delivery of a right arm wrist spin bowler will be to release the ball such that, to a right-handed batsman, the ball spins from the leg side to the off side on pitching, spinning away from the batsman. The bowler holds the ball predominantly between the first three fingers and thumb. When releasing the ball the fingers and wrist rotate around the ball in an anticlockwise direction from the perspective of the bowler. The third finger grips the ball while rotating and the ball leaves the hand from the back of the wrist, away from the thumb (Hughes, 2001).

The majority of the spin generated by a wrist spinner comes from the rotation of the wrist. This enables the bowler to vary the angle of rotation of the ball through a change in the rotation angle of the wrist. This can be effectively concealed from batsmen and is therefore a valuable weapon for the wrist spinner, looking for a false shot to be played (Philpott, 1995).

There are four primary variations employed by wrist spinners, the stock leg break delivery that turns away from the right handed batsman, the slider which will dip in the air and deviate less than the leg break with increased bounce, the googly which turns towards the right handed batsman's leg side and the flipper, a back spinning delivery that keeps low after bouncing straight on and can slow post contact with the pitch (see figures 2.3.8 (a)-(d)).

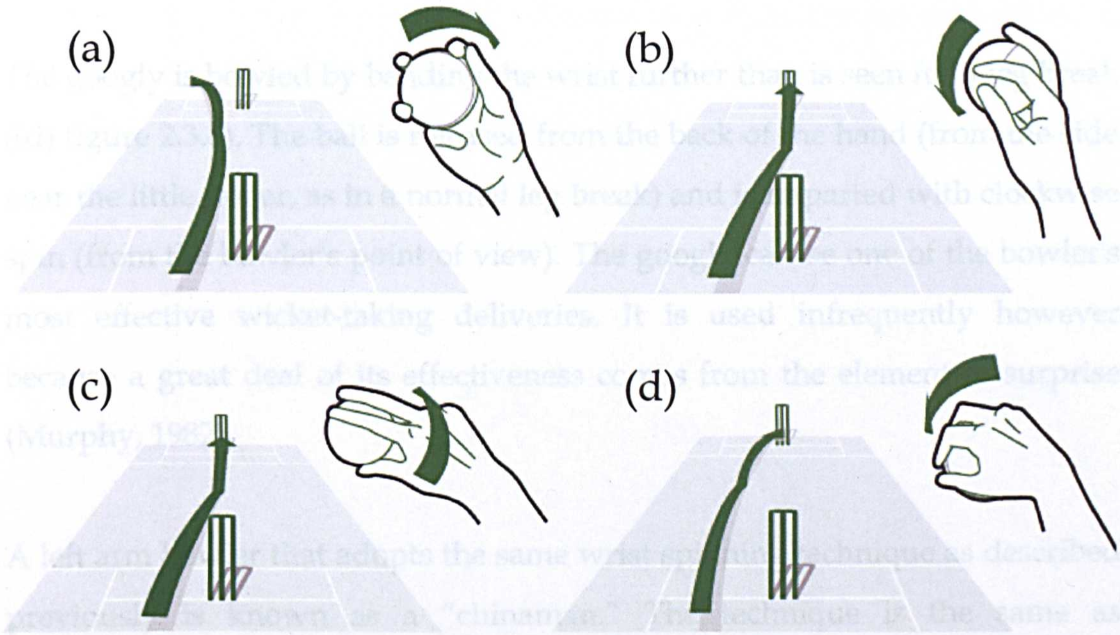


Figure 2.3.8: The grip and hand rotation from a batsman's perspective and typical trajectory of the four main delivery variations seen in wrist spin bowling. The leg break (a), the slider (b), the flipper (c) and the googly (d) (BBC Sport, 2008).

The action to produce a standard leg break delivery for a right handed bowler is a turning of the first three fingers over the top of the ball from left to right (Philpott, 1979) as a batsman would view, bringing the hand down the inside of the ball (Brayshaw, 1978) (see (a) figure 2.3.8).

The first of the variations considered is the slider ((b) figure 2.3.8). The ball is released with the same action as the standard leg break, however, the wrist angle is altered in order to impart more topspin onto the ball. This results in a more "looping" ball flight with the ball bouncing higher, faster and with less lateral deviation than a leg spin delivery (Philpott, 1995).

For the flipper, the bowler holds the ball between the two first fingers and thumb and squeezes the ball out by "snapping" the fingers together down the back of the ball. This imparts backspin onto the ball resulting in a low, skidding delivery (see (c) figure 2.3.8).

The googly is bowled by bending the wrist further than is seen for a leg break ((d) figure 2.3.8). The ball is released from the back of the hand (from the side near the little finger, as in a normal leg break) and is imparted with clockwise spin (from the bowler's point of view). The googly can be one of the bowler's most effective wicket-taking deliveries. It is used infrequently however because a great deal of its effectiveness comes from the element of surprise (Murphy, 1982).

A left arm bowler that adopts the same wrist spinning technique as described previously is known as a "chinaman." The technique is the same as previously described for a wrist spinner, however the ball spins in the opposite direction for each of the variations described. This style of bowler is very rare however, with very few recognised exponents in recent times, notably Michael Bevan and Brad Hogg of Australia and Paul Adams of South Africa.

2.3.4.2: The Finger Spin Bowler:

The action of a finger spin bowler does not typically impart such a high level of spin onto the ball as a wrist spin bowler (Illingworth, 1979). As a result the ball does not generally deviate as far off the pitch as a wrist spinner. To compensate for this the top class finger spinner will vary his deliveries using a wide range of speeds and trajectories.

The ball is predominantly held between the first two fingers with the thumb supporting the ball underneath (see figure 2.3.9). The fingers are spread wide and placed across the seam of the ball to gain maximum grip and leverage when flicking the ball on release (Emburey, 1989). The ball is spun when the fingers and the wrist rotate together. When the ball bounces it deviates to the left or right depending on the bowling arm of the bowler. Right arm finger spinners (off spinners) deviate the ball towards a right handed batsman's leg side. Conversely, left arm finger spinners (left arm orthodox) deviate the ball towards a right handed batsman's off side. The level of deviation which is achieved is dependent on a number of factors including the pitch condition, which part of the ball makes contact with the pitch and the level of spin imparted upon the ball (James, 2005).

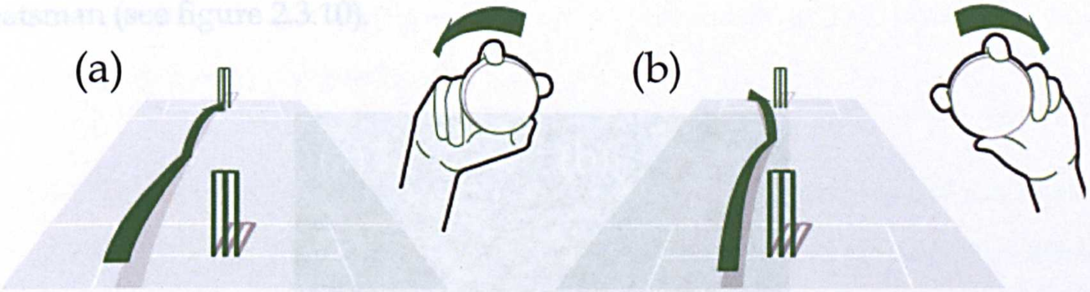


Figure 2.3.9: The grip and hand rotation from a batsman's perspective and typical trajectory of the two variations of finger spin. Off spin (a) and left arm orthodox (b) (BBC Sport, 2008).

The finger spinners' variation focuses upon the trajectory and pace of each delivery, however there is also an "arm ball" variation where the ball swings away from the right handed batsman and carries on along its natural path rather than deviating on contact with the pitch. The ball is imparted with little or no spin with the seam in an upright position. One aim of the arm ball is to make the batsman play at the ball and catch the edge of the bat and carry to the slip fielders or wicketkeeper (Culley, 1997).

Until very recently, finger spin bowlers had been seen as a relatively benign weapon that were used to slow down run rates and progress through overs quickly in the one day form of the game (Wilkins, 1991). Off spinner's wicket taking rates had suffered due to the better preparation of pitches and the use of covers meaning the pitches were dryer and therefore less likely to turn using a finger technique (Wilkins, 1991). The emergence of two off spinners in the early 1990's, Muttiah Muralitharan of Sri Lanka and Saqlain Mushtaq of Pakistan altered this perception. Muralitharan and Saqlain developed techniques that meant batsmen found it very difficult to pick which delivery type was going to be released from the hand. They both had a "mystery ball" (Hughes, 2001) or a "doosra" as it has been named, that was delivered using what appeared an off spin action but produced a ball that turned in the opposite way (i.e. from right to left). Both bowlers used the off spinning action, however the ball was released with the back of the hand facing the batsman (see figure 2.3.10).

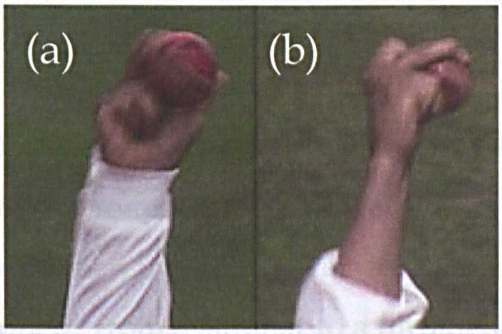


Figure 2.3.10: The off break action (a) and the "doosra" (b) from a batsman's perspective (Morgan-Mar, 2007).

2.4: The Aerodynamics of the Cricket Ball

The cricket ball is a non-spherical object with a seam protruding 0.5-0.8 mm above the surface of the ball, 19.5-21.0 mm wide (BS 5993:1994). The air that flows around the ball influences its flight. The flow of air acts as a drag force and slows the ball throughout flight. By manipulating the orientation of the ball, the spin rate and the speed at which the ball is released, a bowler is able to control the flight of the ball by harnessing these drag forces.

Air flow around a ball is described in one of two ways, laminar or turbulent (Mehta, 1980). Laminar flow is where the air flow is streamlined around the ball and there is minimum drag force seen. Turbulent air flow is described as chaotic and irregular resulting in an increased drag force. As the ball passes through the air a thin layer forms around its surface. This layer of air is known as the boundary layer. The boundary layer cannot remain attached to the ball's surface all the way around the ball and will separate at a point. If the point at which the boundary layer separates is equal on either side of the ball then the ball will continue on a straight path. If, however, the location of separation is earlier on one side of the ball than the other then a pressure imbalance will be present resulting in a side force acting upon the ball deviating it from its original path.

The air's transition from a laminar state to turbulent occurs at a critical speed (typically between 70 - 75 mph) that is determined by the surface roughness of the ball. As a rule, the rougher the surface, the lower the critical speed (Mehta, 2006), however when travelling over very smooth surfaces at certain speeds air can be "tripped" from a laminar to a turbulent state by a protrusion or surface roughness. This is the case with a cricket ball where there is a smooth layer (the ball surface) and a rougher protrusion (the seam). When air flows over the seam it creates eddies within the laminar flow forcing it to become turbulent.

In order to make the cricket ball swing, a bowler angles the seam with respect to the direction of motion (see section 2.3.3). The angled seam trips the boundary layer into turbulence on one side of the ball while on the other side the flow remains laminar. The turbulent layer is able to remain attached to the ball for longer due to its increased energy and a pressure differential is created resulting in a side force influencing the ball's flight, this is known as conventional swing (Mehta, 2006, see figure 2.4.1).

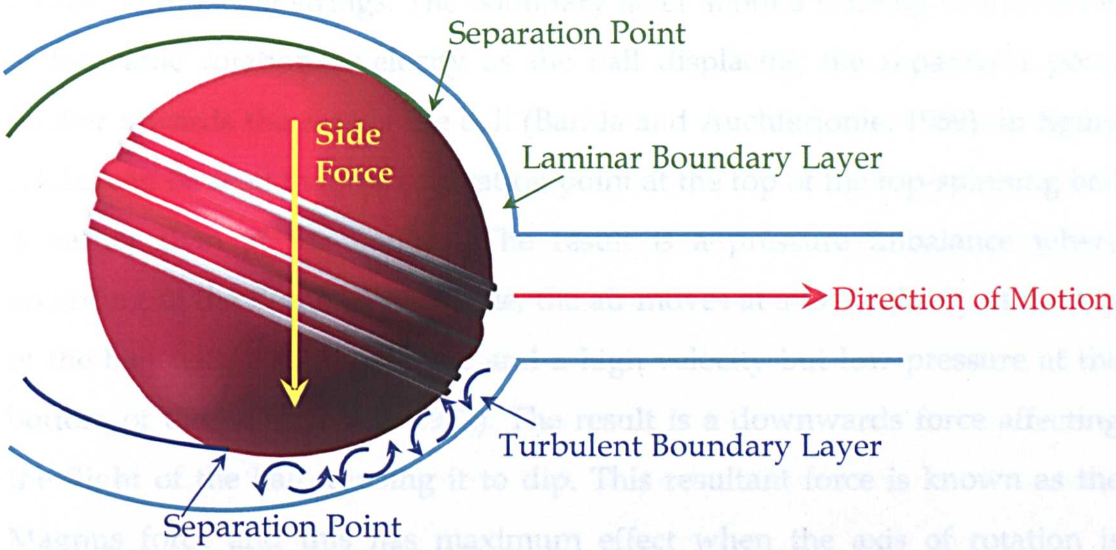


Figure 2.4.1: The air flow over a cricket ball experiencing conventional swing.

The velocity at which the seam will trip the air flow from laminar to turbulent can be predicted using the Reynolds number. Turbulence is defined as the condition when the Reynolds number reaches a critical value. This value is dependent upon the diameter of the ball, the velocity of the air flow and the physical properties of the air such as density and viscosity. The Reynolds number can be calculated using the following equation:

$$R_e = \frac{vd}{\gamma} \text{ where } \gamma = \frac{\eta}{\rho}$$

Equation 1

Where v is the velocity of the ball in m/s, d is the diameter of the ball in m and γ is the kinematic viscosity of the air calculated by dividing the coefficient of viscosity η by the density of the air ρ. For a typical fast paced delivery (85 mph (38.0 m/s)) with a ball of 0.072 m diameter, the Reynolds number would be 1.8×10^5.

The air flow about a rotating ball follows a different model with forces acting upon the ball causing it to either swerve left or right or rise upwards or dip downwards dependent on the rotation of the ball. This was a theory first explored by Isaac Newton who studied the behaviour of a tennis ball post contact with racket strings. The boundary layer about a rotating ball revolves at the same rotational velocity as the ball displacing the separation point further towards the rear of the ball (Barkla and Auchterlonie, 1969). In figure 2.4.2 it can be seen that the separation point at the top of the top-spinning ball is earlier than at the bottom. The result is a pressure imbalance where according to the Bernoulli principle, the air moves at a low velocity at the top of the ball with a high pressure and a high velocity but low pressure at the bottom of the ball (Daisch, 1972). The result is a downwards force affecting the flight of the ball, causing it to dip. This resultant force is known as the Magnus force and this has maximum effect when the axis of rotation is orthogonal to the direction of motion of the ball (Barkla and Auchterlonie, 1969).

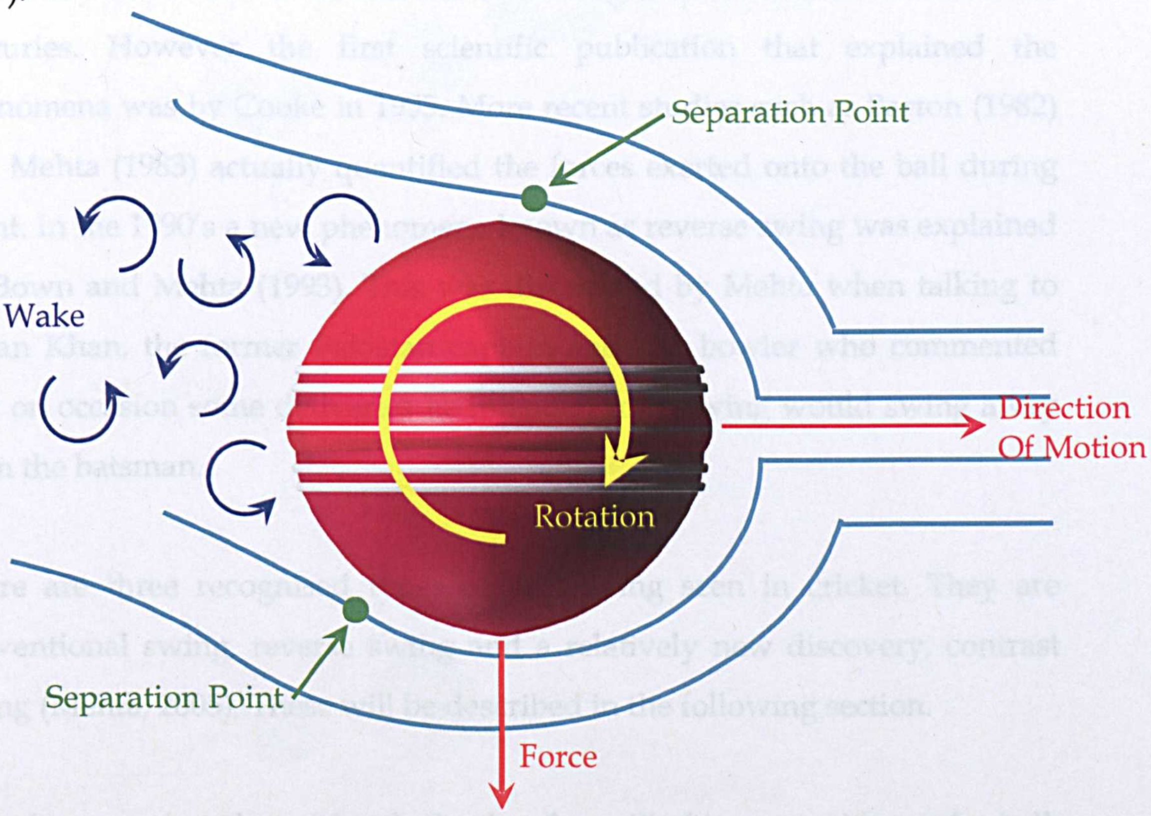


Figure 2.4.2: The air flow around a spinning ball. In this case, the ball is imparted with topspin resulting in a downwards force causing the ball to dip.

There has been significant research conducted to analyse the aerodynamics of sports balls and the effect this has on their flight (Daisch, 1972, Mehta, 1980, Pallis and Mehta, 2003). Sports such as golf and tennis have received particular attention. The surface of a golf ball is dimpled. These dimples trip the boundary layer of air into turbulence enabling the ball to travel further (Mehta, 1985). The consistent behaviour of the golf ball also means that players with high ability are able to exert a high level of control over the ball. In tennis, where the ball is covered in felt, studies have been conducted that show a consistent separation point of the boundary layer, independent of the Reynolds number. One such study conducted by Mehta and Pallis in 2001 concluded that the boundary layer was permanently turbulent around a tennis ball due to the fuzz on the felt of the ball thickening the boundary layer.

The ability of bowlers to deviate the ball in flight has been seen in cricket for centuries. However the first scientific publication that explained the phenomena was by Cooke in 1955. More recent studies such as Barton (1982) and Mehta (1983) actually quantified the forces exerted onto the ball during flight. In the 1990's a new phenomena known as reverse swing was explained by Bown and Mehta (1993). This was discovered by Mehta when talking to Imran Khan, the former Pakistan captain and fast bowler who commented that on occasion some deliveries he intended to in-swing would swing away from the batsman.

There are three recognised types of ball swing seen in cricket. They are conventional swing, reverse swing and a relatively new discovery, contrast swing (Mehta, 2005). These will be described in the following section.

In order to swing the cricket ball a bowler will shine one side of the ball, leaving the other side to remain rough. This enhances the ball's chances of swinging by creating a prolonged rough area on one side of the ball promoting turbulent air flow and a smooth side encouraging laminar flow. As previously discussed, swing is generated by an imbalanced of forces acting upon the ball, achieved by the bowler positioning the primary seam of the ball at an angle to the direction of motion (see figure 2.4.3). The seam trips the boundary layer from laminar to turbulent flow resulting in a delayed separation. The asymmetry of the boundary layer separation results in a pressure differential making the ball swing in the direction the seam is pointing. An illustration of the typical orientation and flight of a cricket ball for in-swing and out-swing deliveries to a right handed batsman is given in figure 2.4.3.

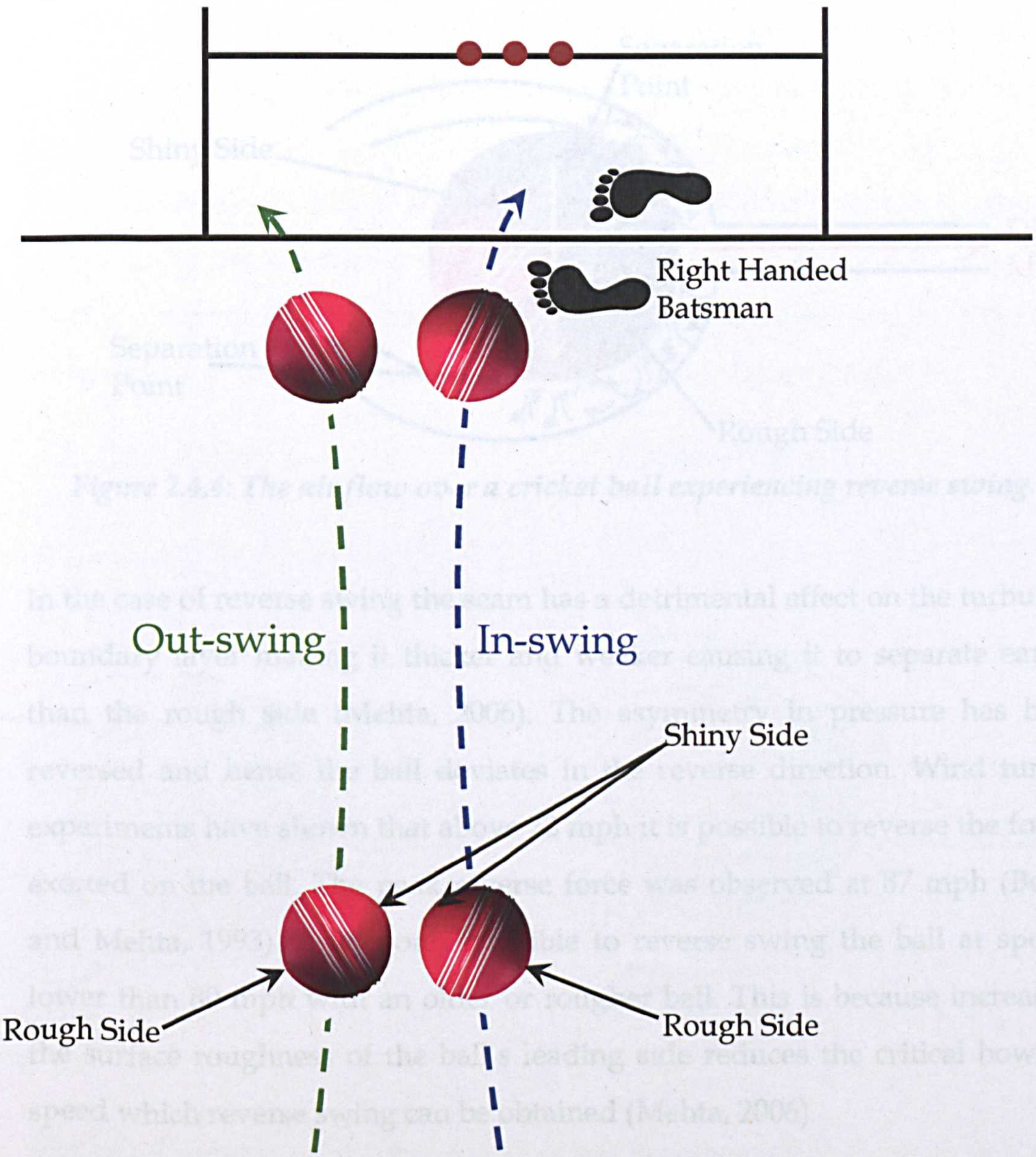


Figure 2.4.3: Typical ball orientation and flight path seen for in-swing and out-swing bowling deliveries to a right handed batsman.

Reverse swing is a term used to describe the phenomena of cricket balls deviating in the opposite direction to that expected under normal conditions (see figure 2.4.1). This type of swing occurs when deliveries are released at high speeds of over 80 mph (Mehta, 2006). At high speeds the boundary layer of air surrounding the ball is tripped into turbulent flow earlier than previously seen for conventional swing. This is important as the air is therefore turbulent before reaching the seam location (see figure 2.4.4).

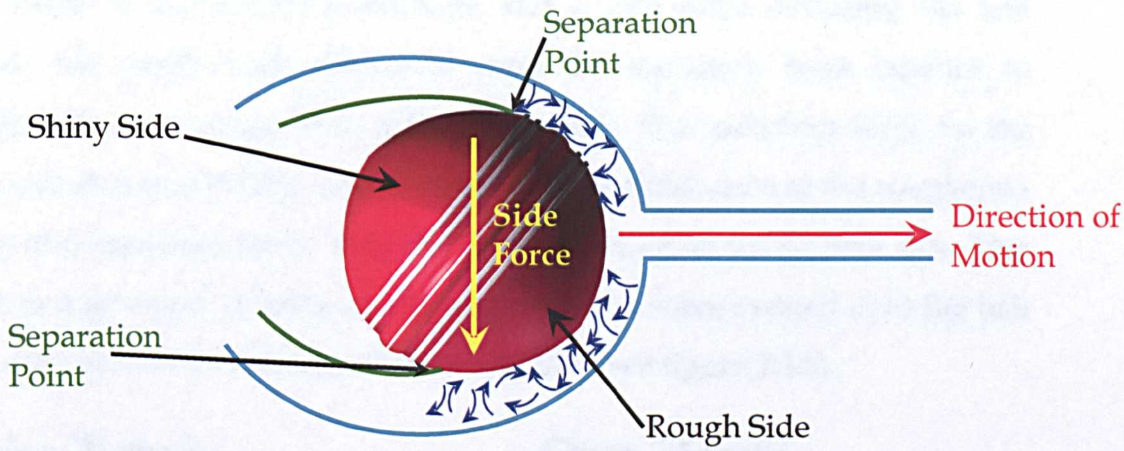


Figure 2.4.4: The air flow over a cricket ball experiencing reverse swing.

In the case of reverse swing the seam has a detrimental effect on the turbulent boundary layer making it thicker and weaker causing it to separate earlier than the rough side (Mehta, 2006). The asymmetry in pressure has been reversed and hence the ball deviates in the reverse direction. Wind tunnel experiments have shown that above 72 mph it is possible to reverse the forces exerted on the ball. The peak reverse force was observed at 87 mph (Bown and Mehta, 1993). It was only possible to reverse swing the ball at speeds lower than 80 mph with an older or rougher ball. This is because increasing the surface roughness of the ball's leading side reduces the critical bowling speed which reverse swing can be obtained (Mehta, 2006).

The third and most recent discovery in cricket ball aerodynamics is known as contrast swing. This was discovered by Mehta on a visit to the ECB National Cricket Centre at Loughborough University in December 2005. Mehta witnessed deliveries bowled with a "straight up" seam deviating in the air towards the smooth side. The direction of this type of swing is determined by the speed at which the ball is released rather than the ball seam and smooth and rough side orientations (Mehta, 2006).

Below 70 mph the laminar boundary layer around the smooth side of the ball separates earlier than the turbulent layer around the rough side of the ball. This results in asymmetrical pressure and a side force deviating the ball towards the rough side. Above 70 mph the transition from laminar to turbulent flow occurs on both sides of the ball. The turbulent layer on the rough side becomes thicker and weaker under the influence of the roughened surface and separates earlier than the turbulent layer on the smooth side. This results in a reversed asymmetry of pressure and a force exerted onto the ball in the direction of the smooth side (Mehta, 2006, see figure 2.4.5).

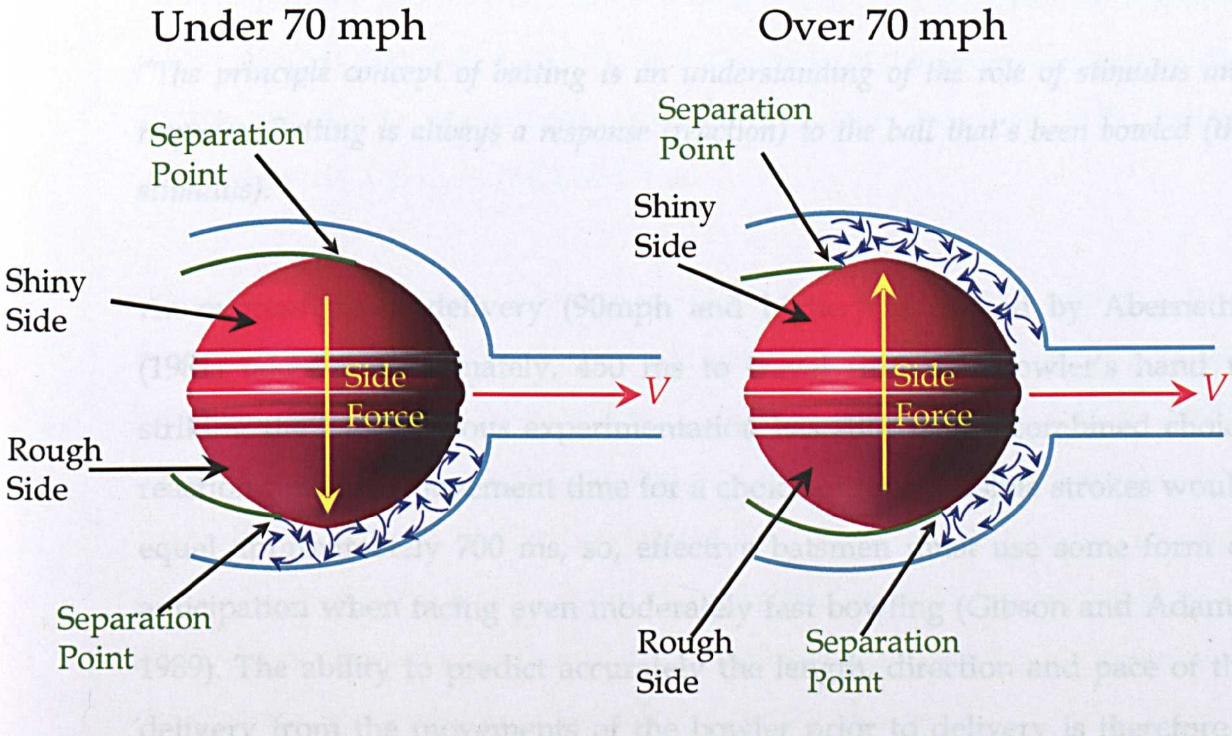


Figure 2.4.5: The air flow over a cricket ball experiencing contrast swing. The side force experienced by ball travelling under 70 mph (left) and over 70 mph (right).

2.5: Cricket Batting

In cricket, the batsman has a wide variety of responses to an oncoming ball. Footwork allows him to position himself with respect to the ball trajectory and the bat can be swung in several different angled arcs to hit the ball deliberately in almost any direction (Morgan-Mar, 2007). Whiting (1969) classified batting in the most complex category of ball skills requiring a ball to be received and sent away in the same movement.

Batting is a skill which demands that the batsman combines visual, perceptual and motor skills to respond to each delivery with a shot selection (Stretch et al, 2000). The skill can be classified as "open" as the batsman must perform under conditions in which the relevant stimuli are changing and perceptual and response uncertainty exists (Poulton, 1957). Chappell (2004) underlines this by stating;

"The principle concept of batting is an understanding of the role of stimulus and response. Batting is always a response (reaction) to the ball that's been bowled (the stimulus)."

An express paced delivery (90mph and higher) as classed by Abernethy (1981) takes, approximately, 450 ms to travel from the bowler's hand to striking the bat. Previous experimentation has shown that combined choice reaction time and movement time for a choice of four possible strokes would equal approximately 700 ms, so, effective batsmen must use some form of anticipation when facing even moderately fast bowling (Gibson and Adams, 1989). The ability to predict accurately the length, direction and pace of the delivery from the movements of the bowler prior to delivery is therefore a skill that greatly enhances a batsman's ability. This skill becomes increasingly important when facing express paced bowlers where the time constraints imposed by ball velocity will typically exceed the time available to process information and act accordingly or high class spin bowlers who are able to disguise the changes in their action that lead to subtly different deliveries (Philpott, 1995). McLeod and Jenkins (1991) reported that if a ball deviates laterally upon bouncing when it is less than 200 ms away from the batsman there is insufficient time for the batsman to alter his shot. Abernethy (1981) recorded spin bowlers releasing deliveries between 17.9 and 26.8 m/s and thus at the slowest of these speeds, if the bowler pitches the ball less than 3.58 metres from the batsman, he must predict the change in direction prior to the ball landing (Renshaw and Fairweather, 2000).

The spatial and temporal events that take place during each delivery are summarised in figure 2.5.1. Abernethy (1981) split the time in which a batsman must react to a delivery (ball transit time (TT)) into three component parts: viewing time (VT), latency time (LT) and movement time (MT). Viewing time represents the time required to detect and recognise stimuli and decide upon the shot to play. Latency time is the delay between the response being selected and the initiation of movement and movement time is the duration between movement commencing and bat and ball contact (approximately 250 msec (McLeod, 1987)).

The movements made by batsmen in cricket are the result of feedback gained from the movements of the bowler and the position of the ball in the bowler's hand and in the air during the delivery (Penrose and Roach, 1995). Information about an individual delivery arising from the movements and anatomical positions of the bowler (Muller, 2006) will be added to prior knowledge the batsman has about the pace and style of the bowler (Sutton, 2007), the pitch conditions (James et al, 2005) and their own form, culminating in a decision being made as to which stroke they elect to play.

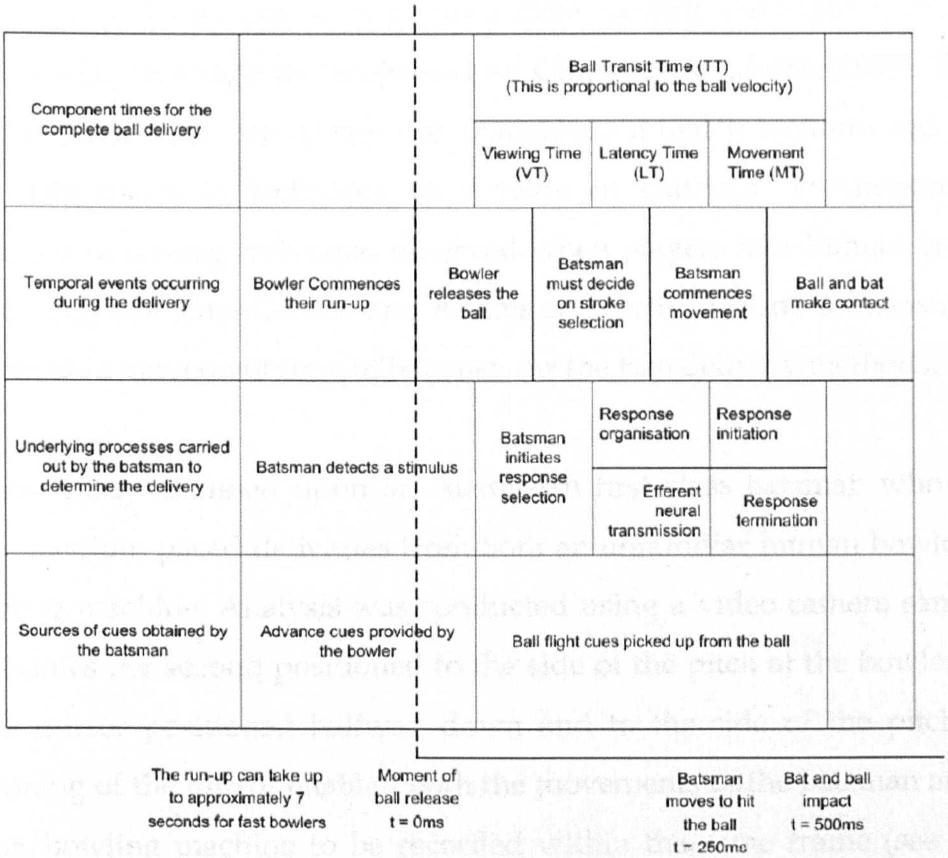


Figure 2.5.1: Factors affecting the delivery and the reaction of the batsman (Justham, 2006)

Using existing bowling machines (see section 2.6) coaches are unable to present batsman with a realistic match environment in which to train. Coaches operating bowling machines typically provide some cue as to the time at which they place the ball in the machine (Gibson and Adams, 1989) usually by raising their hand prior to dropping a ball into the machine. This does not provide batsmen any pre-release information pertaining to ball type, neither does it offer batsmen the opportunity to look for such information.

Some bowling machines operate with warning lights on the front of them usually in the form of a "traffic-light" style countdown to release (e.g. Merlyn). However in a match or when facing a bowler in the nets a batsman must recognise the moment of release during the delivery stride, there are no warning lights or raised hands to help. Further to this, the direction and length of the delivery can be ascertained from viewing the angle of the head of the bowling machine as recognised by Gibson and Adams (1989). This is clearly not a realistic pre-release cue available in a match scenario and could cause deficiencies in technique to develop in batsmen. To measure the differences in batting technique observed when players face human bowlers and bowling machines Gibson and Adams conducted a study to measure the differences in movement time of batsmen for the two delivery methods.

The case study focussed upon an Australian first class batsman who faced twelve medium paced deliveries from both an unfamiliar human bowler and a bowling machine. Analysis was conducted using a video camera sampling at 50 frames per second positioned to the side of the pitch at the bowlers end with a mirror positioned halfway down and to the side of the pitch. The positioning of the mirror enabled both the movements of the batsman and the bowler/bowling machine to be recorded within the same frame (see figure 2.5.2).

Figure 2.5.2: Single frames taken from the video analysis of Gibson and Adams (1989).

The batting stroke was divided into a series of "events." These were identifiable points within the batting stroke that occurred within each shot that could be compared (see figure 2.5.3). The timings of events in the batting stroke and front foot placement are summarised in figure 2.5.3, horizontal lines represent the 95% confidence intervals for each event.

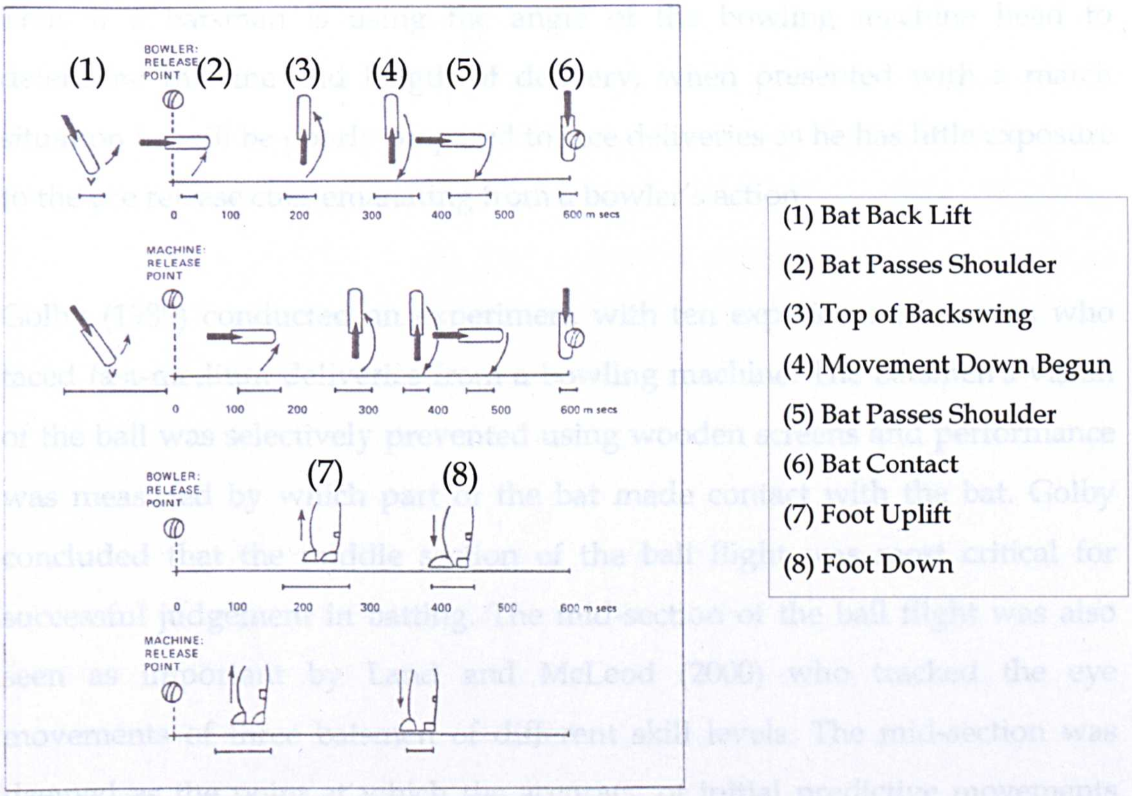


Figure 2.5.3: The timings of events in the batting stroke and front foot placement relative to ball release (Gibson and Adams, 1989).

The results of the test showed that the batsman picked his bat up later and moved his front foot earlier against the bowling machine. The investigators concluded that the differences witnessed in stroke and front foot timing were the result of differences in the batsman's use of spatial and temporal information when faced with the two tasks. Premeditation of delivery length is recognised as the prime reason for early foot movement, with the angle of the bowling machine head a clear indicator of the next delivery's length. Gibson and Adams describe the batsman's situation when facing a bowling machine as *"one of near information certainty"* due to changes in the bowling machine position being easily seen by the batsman.

Abernethy has confirmed that:

"for skilled players, information to help predict the length of a bowled ball is available prior to release" (Abernethy et al, 2005).

Thus if a batsman is using the angle of the bowling machine head to determine the line and length of delivery, when presented with a match situation he will be poorly prepared to face deliveries as he has little exposure to the pre release cues emanating from a bowler's action.

Golby (1989) conducted an experiment with ten experienced batsmen who faced fast-medium deliveries from a bowling machine. The batsmen's vision of the ball was selectively prevented using wooden screens and performance was measured by which part of the bat made contact with the bat. Golby concluded that the middle section of the ball flight was most critical for successful judgement in batting. The mid-section of the ball flight was also seen as important by Land and McLeod (2000) who tracked the eye movements of three batsmen of different skill levels. The mid-section was deemed as the point at which the accuracy of initial predictive movements based on pre-release information was evaluated. This confirms the importance of ball flight characteristics such as launch angle and spin orientation, as it is these that a batsman will use during the mid-section of ball flight to make his judgement.

In cricket, expert batsmen have shown a persistent capability to use early sources of information to aid shot selection which other skill groups are not attuned to (Muller et al, 2005). There are three key abilities developed within the anticipatory skill demonstrated by expert batsmen: (i) visual search: selecting the areas the eyes will focus upon during the delivery stride and release (Land and McLeod, 2000), (ii) selective attention: picking out the key events within the bowling action that relate to ball type (Glencross and Cibich, 1977) and finally, (iii) discrimination ability: being able to recognise the movements of the bowler and interpret them into the resultant ball type (Abernethy, 1993).

It is reasonable to assume that each of these abilities is aided by experience (Renshaw and Fairweather, 2000). Perhaps the area that is most enhanced by experience is discrimination ability where players are provided with a wider store of potentially relevant memories and a rapid and automatic access to these (Schneider and Fisk, 1983). The experience of a player will not however be added to by training with current cricket bowling machines where the information related to anticipation skill is not available (Muller and Abernethy, 2006).

There have been a number of studies conducted to measure the ability of batsmen to judge oncoming deliveries from the actions of the bowler (Renshaw, 2000, Abernethy 2005, Muller 2005). The majority of these studies have been conducted in laboratories and asked batsmen to make a judgement based upon a video of a bowler recorded from a batsman's viewpoint (Muller, 2006, Renshaw, 2000). The work of Muller (2006) is the only example to isolate where this information comes from, concluding that the relationship between the bowling hand and the bowling arm are critical when judging ball type and ball length.

The study conducted by Gibson and Adams (1989) is however the only research concerned with measuring the differences in batting technique witnessed when facing a bowler and a bowling machine. While the experimentation revealed differences in the timing of events during the batting stroke and foot movement, the study was limited due to being conducted in 1989, when equipment was not as advanced as today. One example of this can be seen in the poor clarity of the two stills taken from the video footage recorded featured in figure 2.5.2. The limitations of the available equipment are evident where a single camera (Red Lake Laboratory Locam) was used in conjunction with a mirror to allow for simultaneous recording of the batsman and the bowler/bowling machine. The image resolution is not quoted, however, by using a single camera the resolution of each subject is effectively halved by monitoring both subjects in the same frame.

Perhaps the greatest equipment limitation was the sampling rate of the camera used. A sampling rate of 50 frames per second means that batting stroke events can be measured to ± 0.02 seconds. From the case study presented in Chapter 6, when facing a bowling machine the mean times for the planting of the front foot down and secondary front foot movement up occur within 0.015 seconds of each other (0.229 and 0.244 seconds respectively, see table 6.3.1). This means that analysing images sampled at 50 frames per second could have resulted in this event being missed.

2.6: Ball Launching Technology

Mechanical ball launching devices are used in the coaching and training of a number of sports. The primary use for cricket bowling machines is in net training sessions where batsmen can train alone or with a coach. The use of bowling machines significantly reduces the workload of a team's pace bowlers who can suffer from injuries associated with overuse during a season (see section 2.3.2). Bowling machines can also be used for fielding practice as a means of launching balls into the outfield. The history of bowling machine development is outlined in this section of the literature review and the designs of currently available models are evaluated.

Cricket bowling machines were first introduced in the nineteenth century (Berry, 1987). Nicholas Wanostrocht is the first recorded creator of a bowling machine. His design was based upon a catapult, with a throwing arm attached to project the ball down the pitch (Berry, 1987). During the 1970's the JUGS Company of Australia created the first wheel based bowling machine (JUGS, 2007). Two rubber counter rotating wheels were set just less than a ball width apart. The ball was placed between the two spinning wheels and when contact was made with the wheels the ball was launched. The JUGS Company now make machines for many sports including Cricket, Baseball, American Football and Soccer, all based on this same principle.

The BOLA cricket bowling machine was invented in 1985 (Stuart and Williams, 2008). This was the first ball launching machine specifically designed for cricket and is widely used today throughout all levels of cricket. It adopts the same principle as the JUGS machines, using two counter rotating wheels to propel the ball forwards. The BOLA machine is more compact than a JUGS machine however. This is primarily due to the wheels being of a solid hub construction with a profiled solid rubber coating rather than the inflatable wheels seen in JUGS machines.

A number of ball launching devices are currently available for use within cricket. These devices vary in design and ball launching mechanism. There is however only one machine commercially available that is able to deliver real cricket balls, the Iron Mike pitching machine (Giovagnoli, 1985). This machine was developed for baseball and latterly adapted for cricket by the ECB for use at the National Cricket Centre, Loughborough University.

2.6.1: BOLA

The BOLA cricket bowling machine has been manufactured by Stuart and Williams since 1985. The machine uses two independently driven counter rotating wheels as the ball launching mechanism. The wheels have a solid steel hub with a profiled rubber coating.

Figure 2.6.1: The BOLA cricket bowling machine in use (left) and the head of the machine (right) (Stuart and Williams, 2008).

The BOLA machine is able to be used with real cricket balls, however Stuart and Williams recommends the machine is used with their own dimpled practice balls. These balls are similar to those seen in hockey. The balls have a moulded, dimpled surface on which there is no raised seam as seen in a cricket ball (see figure 2.6.2). The dimples are used to improve the flight of the balls when launched, using the same theory as golf balls where dimples delay the separation of the boundary air layer and induce turbulent airflow over the surface (see section 2.4). The balls are lighter in weight and produce a greater bounce than a cricket ball. One effect of the balls being lighter is a difference for the batsman in terms of "feel" (i.e. impact forces and sound) when the ball strikes the bat. The bounce is also more predictable than a cricket ball due to the absence of a seam. Similar launching machines used in baseball output comparable balls to those used by BOLA. However the baseball equivalent is also endowed with painted, stitch shaped dimples that follow the shape of the stitched seam on a baseball. These allow the batter to analyse the rotation of the ball in flight (ProBatter Sports, 2008).

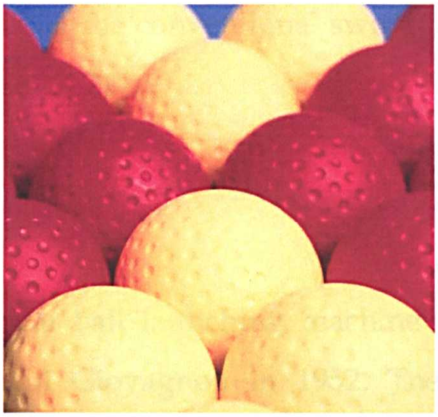


Figure 2.6.2: BOLA dimpled practice balls (Stuart and Williams, 2008)

The BOLA machine is capable of outputting balls from 15 mph up to 95 mph and is able to impart spin onto the ball by offsetting the individual speed of the drive wheels. The spin imparted is not representative of human bowled deliveries unless the head of the machine is rotated 90 degrees about the Y-axis (see figure 2.6.3) such that the drive wheels are vertically aligned. This position could result in topspin and backspin being imparted onto the ball (about the X-axis), representative of some human deliveries, however imparting rifle style spin seen in spin bowling (about the Y-axis, figure 2.6.3) is not possible from a two wheeled configuration.

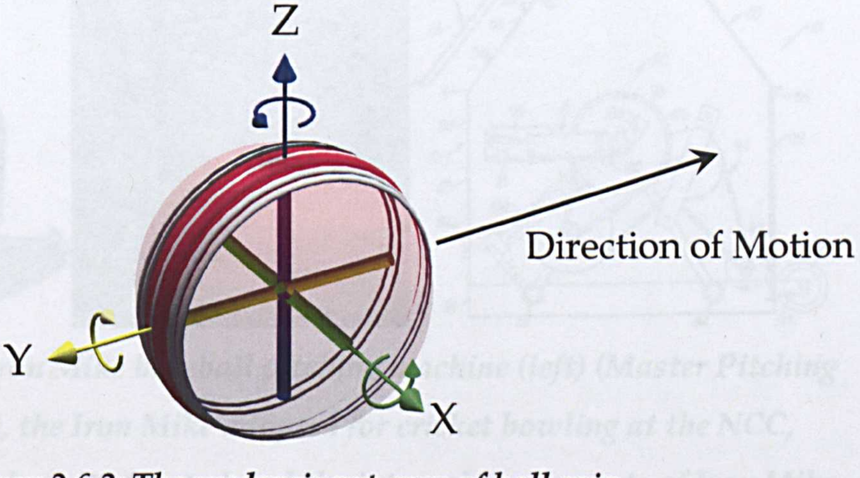


Figure 2.6.3: The predominant axes of ball spin.

Offsetting the drive wheel speeds of a BOLA machine results in a ball rotating about the Z-axis (see figure 2.6.3), this would induce the ball to deviate laterally in the air, not using the conventional swing theory, but experiencing Magnus forces (see figure 2.4.2).

2.6.2: Iron Mike

Iron Mike is a mechanical ball launching machine originally designed for baseball pitching by Paul Giovagnoli in 1952. The version commercially available today was patented in 1985 (Giovagnoli, 1985). The design incorporates a rotating arm with a concave "hand" on the end. This arm is rotated by a chain that is under tension. The level of tension is determined by a spring controlled by the machine operator. This dictates the speed of ball release, the greater the tension in the system, the faster the ball is released. The Iron Mike has been adapted to replicate cricket bowling by the ECB at the National Cricket Centre, Loughborough University. The machine has been raised up and housed on a wheeled support frame to enable ball release from a realistic height and to increase portability within the facility (see figure 2.6.4).

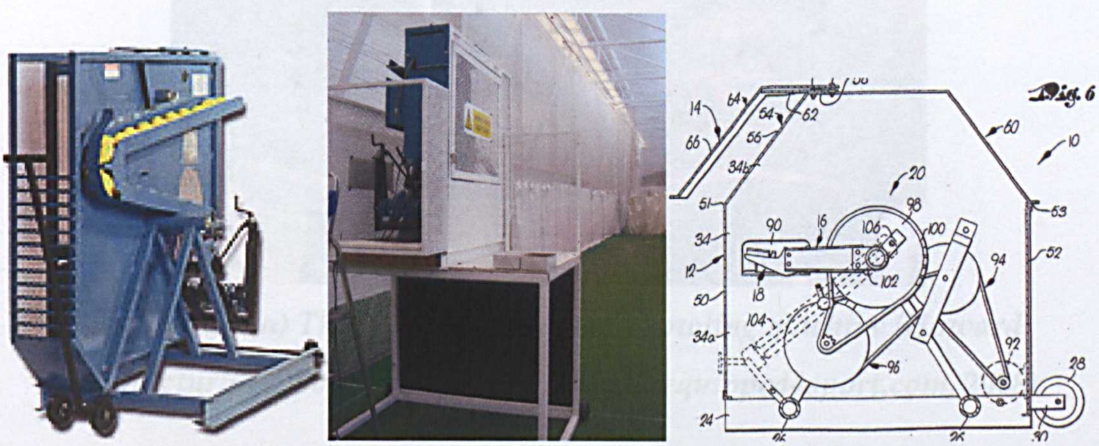


Figure 2.6.4: The Iron Mike baseball pitching machine (left) (Master Pitching Machine, 2008), the Iron Mike adapted for cricket bowling at the NCC, Loughborough University (centre) and the internal components of Iron Mike (Giovagnoli, 1985).

The Iron Mike is capable of releasing cricket balls, however the balls cannot be oriented controllably. This is due to balls being fed into the machine via an automated rack that positions the balls, one at a time in the "hand" of the mechanical bowling arm. The rack can hold up to 38 balls and thus the Iron Mike enables batsmen to train alone, facing 38 deliveries in each session. The manufacturers of the machine claim the machine offers batters a realistic cue of watching the arm and release of the ball to enable training of timing and weight shifting when hitting the ball.

2.6.3: Kanon

The Kanon cricket bowling machine is an air powered machine manufactured by Howard Manufacturing, Port Elizabeth, South Africa (Howard Manufacturing, 2008). The machine uses compressed air fired behind the ball to accelerate the ball and alignment tubes to guide the ball and control the trajectory (see figure 2.6.5).

Figure 2.6.5: (a) The Kanon air powered bowling machine (Howard Manufacturing, 2008) and (b) the Slazball (equipped4sport.com, 2008).

The machine is able to output softballs, tennis balls and dimpled balls. The manufacturer recommends the use of Slazballs (see figure 2.6.5), these are 3.5 ounce balls that have the appearance of tennis balls, however they have a firmer structure aimed at replicating the bounce of a cricket ball (equipped4sport.com, 2008).

2.6.4 Merlyn

Merlyn is a bespoke cricket bowling machine designed by Henry Pryor (Merlyn, 2006). The machine was used by the England cricket team in preparation for facing the Australian leg spin bowler, Shane Warne in the 2005 Ashes series. Merlyn is a unique design, using four independently driven rotating wheels that both launch and spin the ball. In 2005, Merlyn had been the subject of fifteen years of development and as such was still a working prototype. The machine was designed primarily for the replication of spin bowling deliveries although the inventor claims it can release pace deliveries as well. A combination of offset wheel speeds and angled wheels imparts spin onto the ball. The machine has been programmed to release a number of stock deliveries including leg break and googly. Two photographs of Merlyn can be seen figure 2.6.6 taken when the machine was present at the ECB National Cricket Centre.

Figure 2.6.6: The Merlyn bowling machine.

Merlyn can be broken down into two component parts: the central console and the head of the machine (see figure 2.6.6). The central console contains the electronic components and motor drives as well as the screen for the user interface. The head of the machine is the housing for the four counter rotating wheels and the motors that drive them. Balls are fed into the machine via a chute that protrudes from the top of the machine head (see figure 2.6.7).

Figure 2.6.7: Merlyn's ball feeding device.

Balls are fed in at the top of the chute by hand and drop into the machine input position using gravity. The balls drop into position one at a time from the chute, this is controlled by an automated stopper at the end of the chute. Once in the input position, the balls are fed into the wheels using an automated hammer style device that continues to push the ball forwards until it grips between the wheels and is launched from the machine.

Merlyn has been credited with imparting a high level of spin onto the ball (Flintoff, 2005). However, one disadvantage of Merlyn is that at the time of writing, balls are fed into the machine in an unknown orientation. Once fed into the launching wheels the orientation of the seam is not known and will often not be correct for the delivery type selected and hence the desired spin imparted onto the ball. The result is that most balls released from the machine are imparted with a scrambled seam in flight.

When the ball is released with a scrambled seam it becomes increasingly difficult for a batsman to pick which delivery type has been bowled. Although this is a tactic employed by some bowlers for occasional deliveries (Sangakkara, 2007), this is not typical of the majority of spin deliveries faced by batsmen. When this is considered along with the high level of spin imparted onto the ball the batsman is often left guessing as to which shot to play. England's Andrew Flintoff is quoted as saying:

"The ball just pops out of a hole and the two guys who invented it stood there laughing while we tried to figure it out" (Flintoff, 2005)

This implies that, due to a lack of information available prior to the ball being released, he and his teammates found it very difficult to judge oncoming deliveries.

Shane Warne, the bowler the machine was designed to emulate, believes Merlyn could have an adverse effect on batsmen facing the machine. Speaking prior to the 2006/7 Ashes series:

"I think it helps me....because it does these silly things with balls that spin that far and people say 'How do I play that?' and that helps me. So the more they use that the better I reckon." (Warne, 2006)

This suggests that the high level of spin imparted onto balls was not representative of the deliveries batsmen would face and that training against a machine such as Merlyn could leave batsmen questioning their ability.

There is a traffic light style light array on the front of the machine that provides the batsman with a count down warning for when the ball is going to be released. However, without the visual cues emanating from the movements of the bowler, the batsman is using alternative information to judge the line and length of the delivery and thus not training in a realistic environment. Flintoff adds:

"The problem is....you have no chance of picking it (the delivery) with no arm coming over and no hand to watch." (Flintoff, 2005)

This underlines the importance of providing the batsman with information pertaining to ball type and the reliance placed by batsmen on the bowlers movements when judging the timing of their own movements.

2.6.5: ProBatter

Due to the larger amounts of money in the game of baseball (2008 Baseball World Series winners prize money = $18.4 million (Bloomberg, 2008) vs. 2008 Cricket County Championship winners prize money = £100 thousand (ECB, 2008), extra investment has been made into the technological side of the game in comparison to that seen in cricket. As a result the pitching machines that are commercially available are more advanced and greater in number than cricket bowling machines.

One of the most advanced designs of a baseball pitching machine is the ProBatter Professional pitching system. This design has programmable motor control that allow the operator to select a number of pitches to be output in sequence. The system uses a three wheel mechanism to launch the ball (see figure 2.6.8), the manufacturer claims this gives greater control over the ball's launch angle and speed. The pitches output include curve balls and pitches with spin imparted as a result of offsetting the speed of the drive wheels. The programmability of the machine allows the coach to focus on the performance of the batter rather than operating the machine. The system and batter are typically housed within a cage to enable safe use in confined spaces and the option of having multiple systems alongside each other.

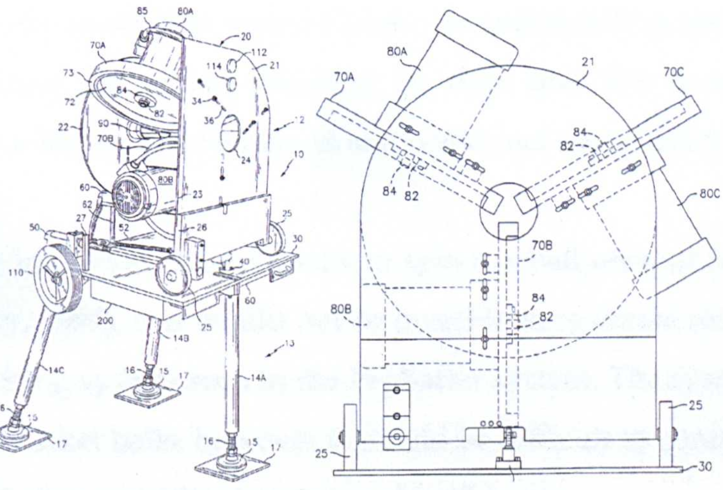


Figure 2.6.8: The three-wheeled mechanical pitching machine in isometric view (left) and front view (right) (Battersby, 2003).

The ProBatter system incorporates a large projection screen into the system design. The screen is positioned in front of the machine as the batter looks down the pitch (see figure 2.6.9). The screen occludes the pitching machine and any movement that may occur when the machine is changing delivery types. From a projector housed in the floor of the batting cage, a video of a pitcher releasing the ball is front-projected onto the screen and is configured such that the hand of the pitcher is positioned over a hole in the projection screen at the point the machine launches the ball. The batsman can therefore use cues from the movement of the pitcher to judge the timing of the shot rather than a countdown of lights as used in some cricket bowling machines.

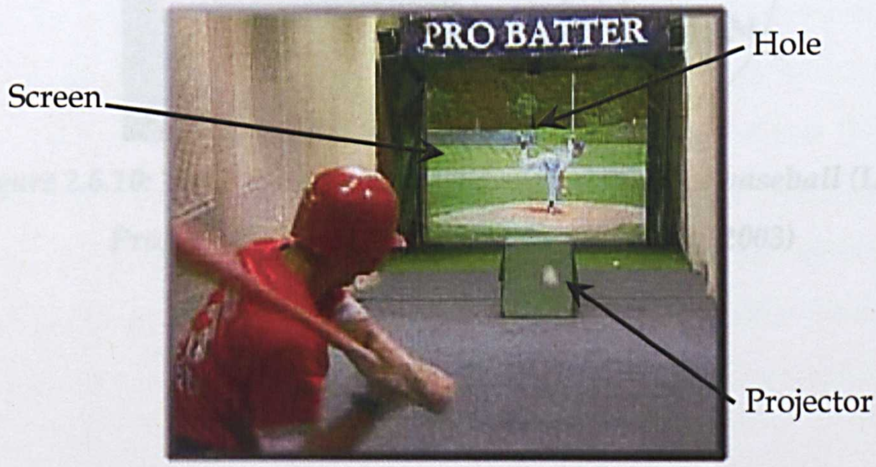


Figure 2.6.9: The ProBatter baseball pitching system. Adapted from ProBatter Sports, 2008.

In order to see the projection screen clearly, the surrounding area needs to be dark. The batting cage must therefore be dark and this is not a natural environment for baseball to be played and could feel unnatural to the batter.

A spin bowler in cricket usually looks to spin the ball around the axis of the seam (Emburey, 1989), this would not be possible to re-create using the three-wheeled launching system seen in the ProBatter system. The system would be able to launch cricket balls, however it would be difficult to control the axis of spin of the ball often resulting in a "scrambled" seam.

The balls used in the ProBatter system are similar to those used in the BOLA cricket bowling machine. They are made from polyurethane with a dimpled outer coating without a raised seam, unlike a baseball. The balls do however have stitch shaped dimples which are coloured to represent the seam and provide the batter with ball orientation information (see figure 2.6.10). The stitch shaped dimples also serve to induce turbulent airflow over the surface of the ball and stabilise the ball in flight (Battersby, 2003).

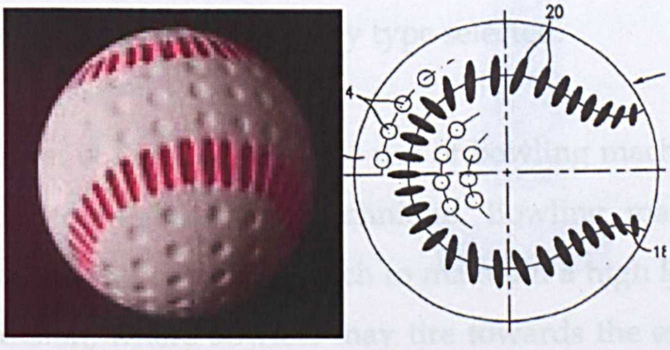


Figure 2.6.10: The ProBatter Sports dimpled practice baseball (Left - ProBatter Sports, 2008. Right – Battersby, 2003)

2.6.6: Discussion

Cricket bowling technique has been documented in numerous coaching manuals (Pont, 2006, Willis, 1984) and biomechanical studies (Elliott, 2000, Lloyd, 2000). There is however a requirement to conduct a detailed analysis of the delivery capabilities of elite bowlers and the ball flight characteristics they impart onto the cricket ball. If a next generation cricket bowling machine is to deliver the entire range of deliveries reviewed in section 2.3 then the range of ball flight characteristics for each delivery variation must be measured.

The importance of ball orientation has been seen throughout this literature review. The variation in the bowler's grip of the ball was a key differentiator between delivery types seen in the review of bowling technique in section 2.3. The review of cricket ball aerodynamics described the influence of the ball orientation on the flight of each delivery (i.e. direction of swing) and the studies conducted by Golby (1989) and Land and McLeod (2000) confirm the importance of ball and spin orientation on a batsman's ability to judge an oncoming delivery. A fully automated cricket bowling machine must therefore detect and orient cricket balls to ensure that they are delivered in the appropriate orientation for each delivery type selected.

Modern day cricket coaches often make use of bowling machines in training sessions to work on a batsman's technique. Bowling machines produce consistent deliveries and allow the coach to maintain a high level of intensity throughout a session, where bowlers may tire towards the end (Noakes and Durandt, 2000). However, the use of a bowling machine to represent a bowler is potentially problematic for the development of a batsman as even though the task involves hitting fast moving balls, the information used to judge oncoming deliveries is not the same in both situations (Muller and Abernethy, 2006).

Currently available cricket bowling machines will perform adequately for coaches to work with batsmen on specific areas of their game that need attention. For training specific shots and teaching muscle memory facing a number of deliveries that behave almost identically is of benefit (Schmidt and Lee, 2005). However current machines do not re-create a realistic match scenario during training sessions. If a batsman is to train for match play effectively, he must train under the same stresses he would face during a match (Chappell, 2004). There is currently no cricket bowling machine capable of imparting a cricket ball with topspin, backspin and rifling spin in a reconfigurable, controllable manner representative of the entire range of bowling deliveries.

Previous experimentation has concluded that top level batsmen gain information from a bowler's movements prior to the ball being released (Abernethy, 1984, Muller, 2006). Without the batsman seeing a bowler running up to the crease and bowling it can only be information gained from the angle of the bowling machine head and ball flight that the batsman uses to judge the line and length of the ball. The case study conducted by Gibson and Adams (1989) provides the only example of the differences in batting technique observed when batsmen are faced with a bowler and a bowling machine. However, the study was conducted in 1989 and with more accurate equipment available there is a need to determine the importance of visual information to batsmen and quantify differences in technique witnessed when faced with the two delivery methods.

It has been established that the visual information about an oncoming delivery gained by top level batsmen prior to ball release differentiates them from lower standard players (see section 2.5). Coaching batsmen to pick up this information could therefore lead to their development. Video based perceptual training has been shown to significantly improve the accuracy of players' judgements in predicting the direction and speed of serves in tennis

(Farrow and Abernethy, 2001). Receiving a tennis serve is a task similar to that of cricket batting (Whiting, 1969), suggesting that the use of a visualisation screen to accompany a bowling machine could be beneficial in cricket coaching. Another method of providing the batsmen with visual information could be the use of head-mounted displays such as goggles. However, Patrick et al, (2000) showed that there was not a significant difference in performance between those that used head mounted displays and those that used projection screens when analysing information, suggesting that the use of visualisation screens is a more cost effective option offering the same level of performance. Maximising external validity when training is encouraged by coaches (Chappell, 2004, Woolmer, 2006) and the use of a visualisation screen would reflect this in comparison to alternatives such as head mounted displays.

A design solution similar to the ProBatter baseball pitching system could be translated to cricket where the batsman would be provided with a visualisation of a bowler running up and delivering the ball. This would provide the batsman with relevant information for the shot selection and timing process from the sources he would receive in a match.

In addition, a cricket training system should provide the user with a programmable series of deliveries offering the variations of delivery discussed in section 2.3 together with a corresponding visualisation to be presented for each delivery type such that the batsman can obtain visual delivery cues. In order to deliver a machine capable of a programmable series of deliveries, analysis must be undertaken of the performance and strategies of elite level bowlers under match conditions to determine the delivery types bowled and the strategies used in match play.

3: Quantifying Cricket Bowling

In order to provide a batsman with a match realistic environment in which to train, it is imperative that any deliveries from a bowling machine have the same physical characteristics as those released by human bowlers. There are two key reasons for this: (i) so that the ball behaves as it would through the air and post contact with the pitch and (ii) the ball must be released from the correct position, in the correct orientation and rotating about the correct axis for each delivery type if "delivery type" information is to be gained by the batsman during the early flight of the ball. Previous research has established that there are key delivery cues (e.g. grip, wrist position) that can be determined from the run up and anatomical position of the bowler prior to release (Muller et al, 2007. Abernethy et al, 2006). This information has led to the requirements of a visualisation that accompanies a training system and is discussed in Chapter 7 of this thesis. This chapter is however focused upon the determination of the performance of human bowlers and the flight characteristics of the deliveries they release with the aim of addressing the following research questions:

- What are the key variables required to recreate a cricket bowling delivery?
- What are the most suitable methods available to analyse cricket bowling?
- What are typical ball flight characteristics of human bowled deliveries?
- How do these flight characteristics change with delivery variations?
- What is the range of delivery parameters required by a programmable bowling machine?

3.1: Identification of the required variables

In order to recreate human deliveries accurately, seven key variables have been selected that it is hypothesised would enable the complete characterisation of each delivery type: (1) the release position in 3-D space, (2) the ball speed, (3) the ball orientation at release, (4) the ball spin rate, (5) the predominant direction of spin, (6) the vertical launch angle of the ball and (7) the pitching position of the ball.

The position at which the bowler releases the ball provides the batsman with information pertaining to the type of delivery being bowled. One example where this is particularly evident is when a batsman faces a "bouncer" from a fast bowler. For these deliveries, the ball is released later (and hence lower in 3D space) during the delivery stride in order to impart a steeper launch angle onto the ball causing it to pitch at a shorter length down the wicket. A batsman must therefore analyse the position of the bowler's hand at release if he is to anticipate the shorter delivery.

Spin bowlers often vary the position at which they release the ball. Due to spin deliveries being slower, it is important for bowlers to feature as much variation in their range of deliveries as possible to maximise the number of potential deliveries a batsman may face. During a test match, due to the longer nature of the game, there is more potential for a bowler to experiment with his deliveries. Three still images taken from television coverage of an England test match (see figure 3.1.1) illustrate three different release positions of an England spinner with (from left to right) a wide release, a central release position and a release close to the stumps.

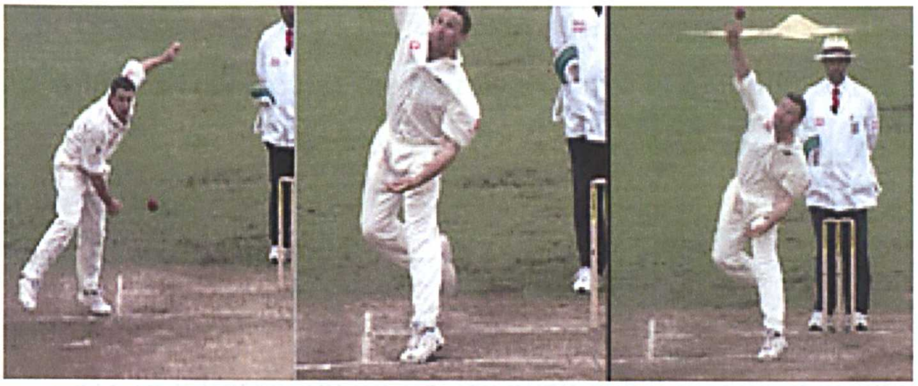


Figure 3.1.1: An International off-spinner displaying various release positions adopted during a match; (from left to right) wide of the crease; in the middle of the crease; tight to the stumps (Hughes, 2001).

By varying the point of release and using the width of the crease, the bowler is able to use various angles of delivery against a batsman. A typical incentive to release the ball from a wider position is the chance to pitch the ball into rough patches on the wicket outside the right-handed batsman's leg stump. The roughened patches fall in line with the bowler's wider release position and the batsman's stumps. Landing the ball in these areas increases the chance of lateral deviation and unpredictable bounce due to nature of the deteriorated surface thus increasing the chance of a wicket for the bowler.

The speed of the ball at release dictates the time during which the batsman will need to sample and analyse information, make a judgement based on this information and act upon it by playing a shot. A more in depth view on the demands placed upon a batsman is presented in Chapter 6, however, in brief, the speed of the ball plays a key role in the shot selection process and will often dictate the number of shots available for selection to a batsman.

The orientation of the ball at release and the speed and axis of spin during the initial ball flight gives the batsman information pertaining to delivery type. This is of particular relevance when facing a spin bowler whose variations of delivery are usually manifest in the manipulation of the ball's spin axis relative to the position of the seam. Due to the technique exhibited by the majority of bowlers who hold the ball with their fingers placed around the seam and spin the ball around the seam's axis, the orientation of the seam at which the ball leaves the bowler's hand is also often the major source of information for batsmen.

The vertical angle at which the ball is launched from the bowler's hand is an important piece of information for the batsman when making a judgement on the ball's pitching length. The length of the ball determines whether he should move forwards or backwards in the crease to play a shot. As this decision must be made early in the shot selection process, a rapid analysis of the ball's trajectory is essential.

Finally, the pitching position of a delivery must be appreciated as this will effect the shot selection of a batsman. Typically, a spin bowler will pitch the ball further down the wicket than a fast bowler. An explanation for this could be that there is a greater chance of a batsman making a mistake when a ball moves laterally off the pitch a short distance in front of him. It is thus important to have spin and pace deliveries pitching at their realistic distances down the pitch.

3.2: Measuring the launch conditions of sports projectiles

Measuring the launch conditions of projectiles has been the subject of previous research covering a range of sports and utilising a number of methods. In this section, popular analysis systems and techniques adopted by other investigators have been summarised with respect to the advantages and disadvantages of applying these methods to the analysis of cricket deliveries.

3.2.1: Radar Gun:

Radar guns have been used extensively to quantify the release speed of deliveries in case studies focussing upon cricket bowling performance. These notably include Portus (2000) who studied the physical differences in bowlers' actions during an eight over spell using orthogonal 50 Hz cameras. The release speed and accuracy of each delivery bowled were measured, a radar gun was used for the ball speed and a zoned scoring target used to evaluate accuracy. Taliep (2003) studied the accuracy and pace of fast bowlers during a twelve over spell in an indoor facility using a radar gun positioned 25 metres behind the bowler's stumps to measure release speed. Radar guns employ the Doppler Effect (JUGS, 2007) to calculate the speed of the selected object in the path of the beam.

If the release speed was the only variable of interest then a radar gun would appear to be a good solution as it produces accurate values when measuring typical cricket bowling release speeds (i.e. 22.22 m/s - 38.9 m/s (Taliep, (2000)) and has minimal intrusion on the training or match being undertaken. However no other parameters are derived from the sampled data and thus a radar gun would have to be used in conjunction with other analytical equipment if the full range of required variables (see section 3.1. above) are to be determined.

3.2.2: Trackman (Radar):

Trackman is a system derived from military missile tracking technology using Doppler radar principles (trackmangolf.com, 2008). The system utilises microwave technology and is able to triangulate the position of a ball in 3D space using three receivers rather than the single receiver seen in a radar gun. The system continually monitors the ball position throughout the entire flight trajectory. The variables calculated by the system are the ball velocity, the vertical and horizontal launch angles of the ball and the ball's spin rate. Additionally lift and drag coefficients can be derived throughout the flight of the ball. The system was initially designed and tuned for the analysis of golf ball trajectories where spin rates of up to 11,000 rpm are not uncommon (Cochran and Stobbs, 1968). In golf the system has proved to be successful however its use in other sports may be limited. For example, one downside is that the manufacturer claims that spin rates under 300 rpm are not measured accurately by the system. This is a problem in sports such as soccer where slower spin rates are commonplace, however in cricket spin rates of approximately 1800 rpm are typically seen. A screenshot of a trackman analysis of two golf shots (left) and the trackman results screen (right) is presented in figure 3.2.1.

Figure 3.2.1: A screenshot of golf shots as analysed by Trackman (left) (Animation Research Ltd, 2007) and the variables analysed(right).

A study was conducted by Tavares (1998) using a system similar to Trackman, measuring golf ball spin decay using radar measurements. A thin metallic circle was glued to the surface of the golf ball and a single receiver radar instrument tracked the rotation of the metallic spot after delivery via a controllable golf ball launcher. The results of the testing included the mean spin rate of the ball, the spin decay of the ball over its flight and the velocity of the ball. Comparisons were made with previous results taken from high speed video analysis (see section 3.2.5 below), with the radar measurements found to be within 2%-4% of the high speed video. From the testing Tavares was able to predict the effects of ball construction and dimple pattern on spin decay below a maximal spin rate of 6000 rpm for a typical 5 iron shot.

A single receiver radar system can be used for measuring ball spin rate around "one axis" as seen typically in sports such as golf and tennis (Tavares, 1998, Pallis, 1998). However spin deliveries in cricket will often spin about three principle (orthogonal) axes: X, Y and Z. To support these measurements a system with three receivers would be necessary, indicating that Trackman could be a suitable option for analysing cricket deliveries. However since the Trackman system was developed for the analysis of golf shots and at the time of selecting a system to analyse cricket bowling within this thesis, the system had not been used to analyse any other sports projectiles, it was not utilised. Nevertheless a recent analysis of a soccer kick using the Trackman system has subsequently been conducted by Ronkainen and Holmes (2008) and is summarised later in this chapter.

3.2.3: Vicon:

The majority of cricket bowling research has been conducted in laboratory-based environments with a focus on the biomechanics of bowler's actions not the deliveries produced. Many of these studies have been carried out to analyse the stresses placed upon the body by the demands of cricket bowling and to evaluate the legality of bowlers' delivery actions. Biomechanical analysis of bowling actions has two further applications: (1) for the coach, who can scrutinise the physical position of a bowler during the delivery stride and make adjustments to a player's technique to optimise performance and (2) for the governing bodies to police the game and ensure that bowlers are conforming to the laws of the game such as maintaining a fixed elbow angle "during the part of the delivery swing which directly precedes the ball leaving the hand" (ICC, 1992). One such study was conducted by Lloyd et al

(2000) who carried out an upper limb kinematic examination of Muttiah Muralitharan using Vicon (see figure 3.2.2). Vicon is a motion analysis system that works by tracking infra-red reflective markers using several cameras. These cameras emit infra-red light from a ring of LED strobes housed about the camera lens. The infrared reflective markers used within the system are reflective balls mounted onto a disc that is then attached, typically, to joint centres upon the test subject as seen in figure 3.2.2. As an instrumented object passes through the capture volume of the arranged cameras, the light from the strobe is reflected back onto a light sensitive plate housed within the camera creating a signal (Vicon, 2002). Typical biomechanical examinations are carried out at sampling rates of 480 Hz as this is the fastest sampling rate maintaining a full image resolution of 1280 X 1024 pixels. The MX-13 cameras used within the system are however capable of sampling up to 2000 frames per second at a reduced resolution.

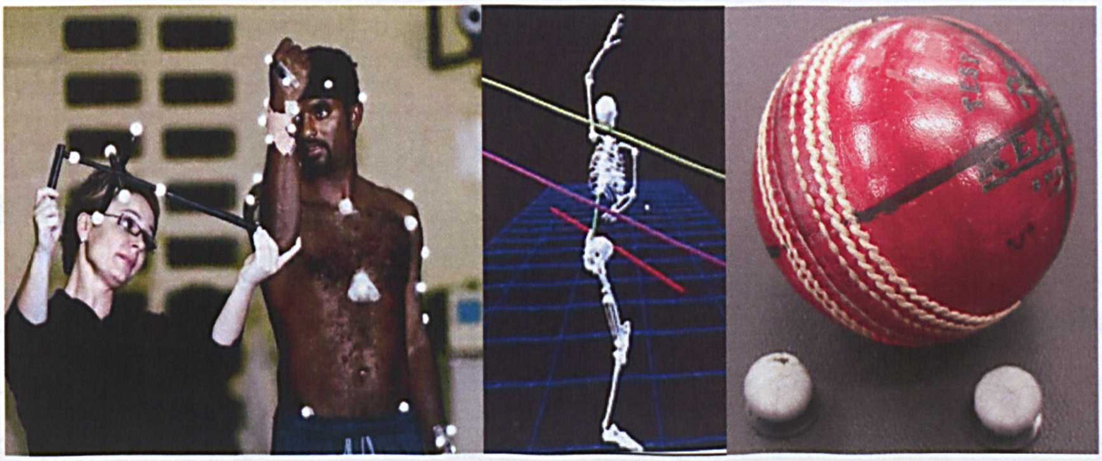


Figure 3.2.2: Muralitharan during a biomechanical study with Vicon markers placed at relevant anatomical positions (left), a typical result of biomechanical analysis (centre) and a cricket ball pictured with typical Vicon markers (right)(Left; Swanton, 2005. Centre; www.bbc.co.uk/sport/cricket, 2006)

Vicon could potentially be used to determine the required trajectory and spin data to replicate a delivery. However currently this is impractical since: (1)

extensive post processing of the 3D co-ordinates would be needed to acquire the delivery parameters, (2) the system requires a lengthy equipment setup in an environment free from daylight and (3) the large 3D measurement area needed to analyse the entire delivery would require large reflective markers placed upon the subject and the ball. Placing markers upon the ball or applying a reflective material to the surface of the ball would create two problems. Firstly the surface of the ball would be altered and hence the player's grip could be affected both in terms of position and friction between the surface of the ball and skin. Secondly, the physical and aerodynamic characteristics of the ball would be altered. For example this could affect the weight of the ball and alter the flight of the ball and the feel in the bowler's hand. A further complication could be maintaining a bond between the ball and the markers when the ball impacts the pitch.

In conclusion Vicon is an excellent tool for the anatomical analysis of the bowler, but is currently impractical for the quantification of ball flight dynamics.

3.2.4: CODA:

CODA is a motion analysis system *(www.codamotion.com, 2008)*. The positions in 3-D space of infra-red light emitting diode markers are measured by bespoke scanning units that are capable of sampling at up to 800 Hz. At the time of testing, the markers were driven by battery packs capable of powering two markers, although an updated system can currently power up to eight markers from one battery pack. These battery packs additionally need to be fixed to the test subject along with the 3-D markers (see figure 3.2.3). The system is able to provide real time high resolution measurement of multiple marker locations without manual data processing or marker trajectory confusion (Harper, 2006). A series of images demonstrating a typical graphical result of CODA analysis of a golfer (left), the instrumentation of a test subject with CODA markers (centre) and two light emitting markers used by CODA and a battery pack pictured alongside a cricket ball (right) are presented in figure 3.2.3.

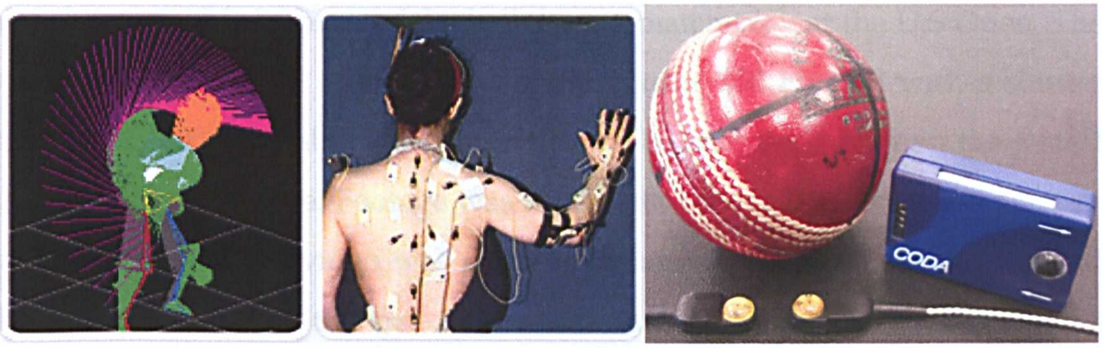


Figure 3.2.3: CODA: graphical result (left), instrumentation (centre) (www.codamotion.com, 2008),two three dimensional markers and a battery pack pictured with a cricket ball (right).

Similarly to Vicon, the CODA system could potentially sample all of the data required, however the markers used by the system are large (see figure 3.2.3), would affect the subject's grip on the ball, would dramatically alter the flight characteristics and there could be issues with markers being obscured from the CODA scanning units during the delivery stride. This scenario was illustrated by Harper (2006) who had difficulty with markers being obscured on golfers' necks during analysis of the golf swing and hence data being lost.

3.2.5: High Speed Video:

High speed cameras are able to sample data at higher frame rates than standard video cameras (i.e. 25 frames per second (PAL) or 29.97 frames per second (NTSC)). Modern cameras are capable of recording up to 650,000 frames per second, achieved by software-controlled hardware within the cameras. For example the electronic shutter controlled by the software within the camera accurately determines when the camera samples data. The cameras are therefore not limited by the inertia of physical components and can achieve higher sampling rates.

In tennis, Pallis (1998) used high-speed video to record the spin rate of the ball and the general behaviour of the ball during match-play at the U.S Open. The system that was used sampled at a frame rate of 250 Hz and with a shutter speed of 1/2000 s enabling a crisp image to be recorded, even on the fastest shots such as the serve. Footage was recorded of the ball as it left the player's racket. Additionally, video was recorded when play had changed ends and the ball passed over the net. The variables that were measured were the velocity of the ball, the angle of flight, the spin rate of the ball as it left the racket, during the flight and before and after the bounce. A peak spin rate of 3751 rpm was recorded for a men's forehand shot, with the player in question averaging over 3300 rpm on all forehand shots played.

A similar experiment was conducted by Carre (2002) who investigated the flight of a spinning and a non spinning football through the air using two high-speed cameras. One camera was positioned at the beginning of the ball's flight, capturing the launch conditions. The second camera was positioned orthogonally to the ball's flight, at a greater distance away, capturing the arc of the trajectory over ten metres. In this testing the cameras sampled at 120 Hz with a shutter speed of 1/500 s. A composite of two frames taken from Carre's testing is illustrated in figure 3.2.4; the trajectory of the ball's flight (left) and the capture of the ball's launch characteristics (right).

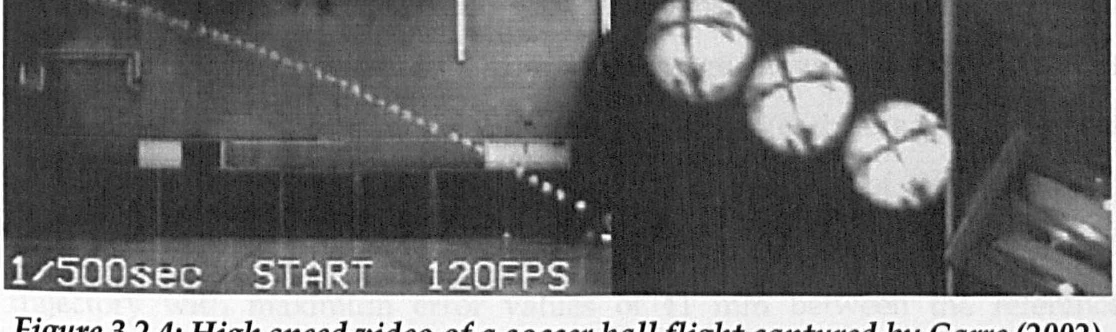


Figure 3.2.4: High speed video of a soccer ball flight captured by Carre (2002).

Using an alternative technique, a study was conducted to quantify the launch conditions of a baseball pitch by Theobalt (2004). The study was carried out with the hypothesis that highly accurate image data could be recorded of the pitcher's action and the initial launch characteristics of the ball without the use of highly expensive equipment such as high-speed cameras while still gaining the same high quality data. The test setup comprised a standard digital camera set to a long exposure time and a stroboscope light that emitted short light pulses at 75 Hz positioned behind the pitchers arm pointing towards the home base. The result of this combination was a superimposed image of the pitcher's hand and ball at a series of stages through the release action. From this a number of measurements were taken to quantify the release characteristics of the ball (e.g. release speed, spin rate). Further tests were carried out to analyse the entire flight of a pitched baseball over a distance of 18.44 m, using four synchronised digital cameras (i.e. two at the beginning of the ball's flight and two capturing the final third of the ball's flight at the home base end). Each pair of cameras had its own stroboscope (80Hz at release, 50 Hz at end of trajectory).

Both the ball and the hand were equipped with multi-coloured markers to allow for motion tracking during analysis resulting in a 3-D reconstruction of the pitcher's hand position during release and the ball's flight over the 18.44 m distance. Speeds of up to 65.7 mph and maximal spin rates of 1623 rpm were reported. Figures 3.2.5 (a)-(d) is a composite of several images taken from the testing of Theobalt illustrating: (a) an image taken using a single digital camera with a long exposure and a stroboscope showing the trajectory of the baseball post release, (b) a computed image showing the movement of the hand during the ball release and early ball flight, (c) the marking up of the pitcher's hand and (d) the complete trajectory analysis of the pitch. The measurements were evaluated against a computer generated reference trajectory with maximum error values of 41 mm between the reference trajectory and measured ball position, 1.9 mph between the reference and measured initial speed and 32 rpm the difference between the reference and measured spin frequency.

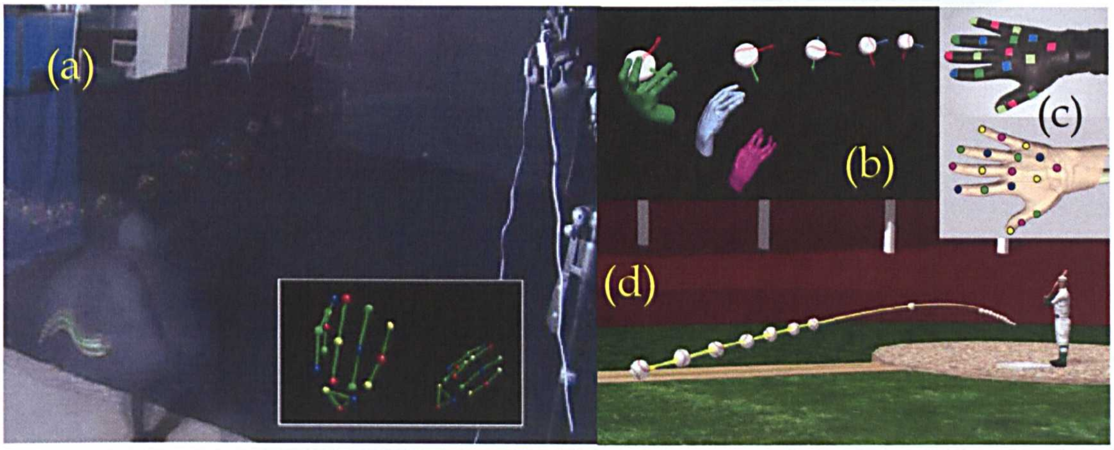


Figure 3.2.5: Theobalt's analysis of a baseball pitch (Theobalt, 2004).

In a more recent study carried out by James et al (2005) studying the playing character of cricket pitches, the release characteristics of bowlers, specifically the ball release speed, vertical launch angle, spin rate and spin axis were determined. Five county standard bowlers were analysed using a Phantom v4 high speed video system sampling at 1000 Hz set up to record the ball as it left the bowler's hand. The sample of bowlers recorded consisted of three medium paced seam bowlers and two spin bowlers. For the medium paced bowlers a mean speed of 30.4 m/s (68.1 mph) was seen with a mean spin rate of 126 rad/s (20.1 rps). For medium paced bowlers the spin imparted is predominantly about the X axis (back spin) (see figure 3.2.6). For the spin bowlers a mean speed of 19.3m/s (43.2mph) and a mean spin rate of 150 rad/s (23.9rps) were recorded. The axis of spin was defined by drawing a line with its origin at the point zero to a finishing point derived by three co-ordinates in X, Y and Z axes. This line represented the principle axis that the ball rotated about. No uncertainty values were quoted.

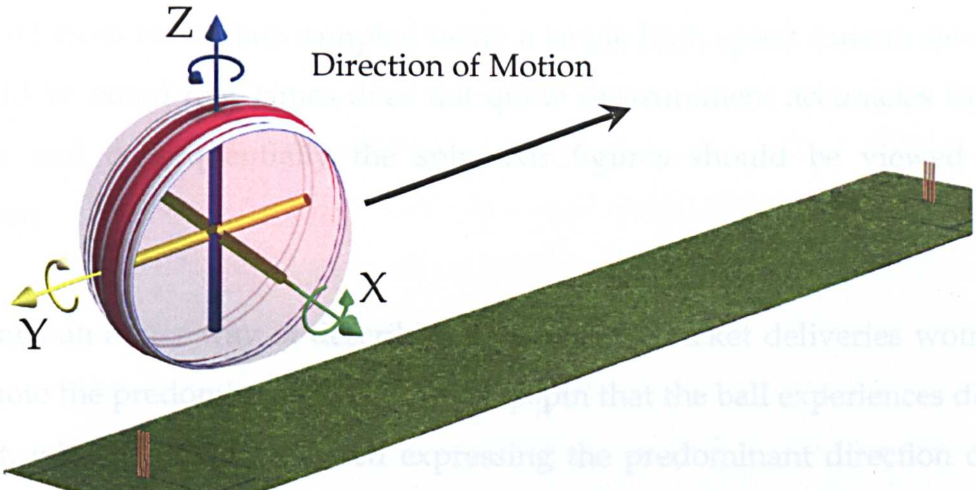


Figure 3.2.6: The three principle axes used to describe cricket ball rotation, X, Y and Z displayed relative to a cricket pitch.

High speed video analysis can be used to provide all of the necessary data for the bowling machine if multiple cameras are used to record subjects within three dimensional space and post processing software is used to analyse the video data. Additional visual information will also be gained of the bowler's action and the methods used to impart spin onto the ball. This analysis would perhaps be the most appealing to players and coaches by providing visual insight into the performance of the players. Caution must be taken with video analysis to ensure that the projectile travels across the field of view perpendicular to the camera to ensure an accurate measurement. This is a concern with the work carried out by Pallis (1998) where, due to the nature of tennis and the recording of match-play from the courtside, there could be a significant error in speed and spin measurements due to the ball moving out of plane when hit from one side of the court to the other. If one camera was used there could also be an underestimation of any spin if the ball is rotating about an axis and that axis is precessing. With one camera it is only possible to measure spin about axes perpendicular to the camera confidently and if that axis is precessing the rotation of the ball could move out of plane. This is an area of uncertainty in the work published by James et al (2005) where an axis of spin is accurately defined using 3-D co-ordinate measurements derived from video data sampled using a single high speed camera set up. It should be noted that James does not quote measurement accuracies for this study and consequentially the spin axis figures should be viewed with caution.

Perhaps an easier way of describing spin seen in cricket deliveries would be to quote the predominant direction of topspin that the ball experiences during flight, with an angle measured expressing the predominant direction of the ball rotation normal to the axis the ball is rotating about. Other than deliveries bowled by pace bowlers and the flipper delivery bowled by leg spin bowlers, cricket deliveries are imparted with directional topspin. The direction of spin can be described as the angle at which a stationary ball would roll if imparted with this spin when viewed from above ((a) figure 3.2.7). The angle (θ) is measured from a plan view with respect to the ball's direction of motion. In figure 3.2.7 the cricket ball is rotating about a known axis, the green bar travelling through the centre of the ball. A cross has been placed at the end of this axis to show the level of rotation the ball is undergoing.

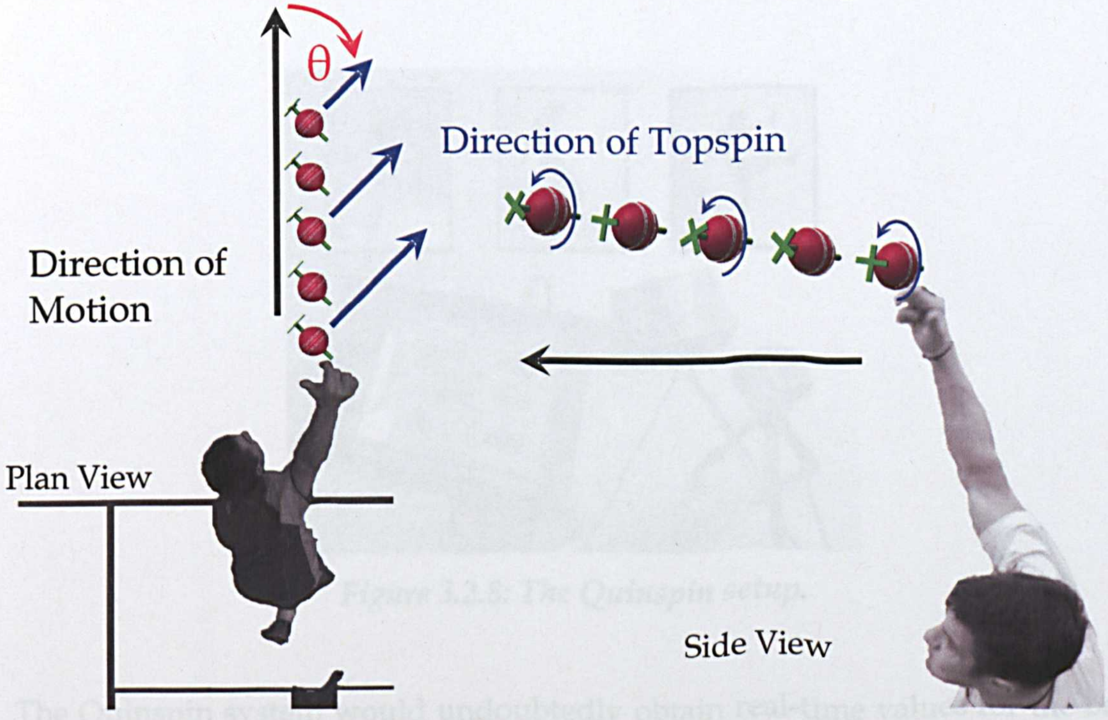


Figure 3.2.7: The release of an off spin delivery with direction of spin expressed as an angle, θ, measured with respect to the direction of motion.

3.2.6: Quinspin:

Quinspin is an image acquisition system developed at Loughborough University primarily for the analysis of soccer kicks (Neilson et al, 2004). The system captures two images of a specially marked ball, one of the stationary ball prior to being kicked and a second image of the ball 6 ms after impact. Using image processing techniques (e.g. colour recognition, image differencing) the system is able to calculate the launch angle and velocity of the ball. The spin rate and spin axis can be found by comparing the position of the ball markings in the two images. These markings are positioned so that the relationship between each one is unique, this means that the initial orientation of the ball is of no consequence to the system and it can compute the required variables based upon the change in marker position from the first image to the second. The system can operate indoors and outdoors with the imaging system positioned 1.25 metres from the ball being measured. The accuracy of the system is quoted as ± 7 mm positional error and ±6.0 rpm when measuring spin rate.

Figure 3.2.8: The Quinspin setup.

The Quinspin system would undoubtedly obtain real-time values for the ball flight characteristics of bowling deliveries. However there would be no data sampled regarding the release position of a delivery and in order to obtain values for ball orientation, post processing of the data would be required. The system has never been used for any sport other than football and is optimised for this domain (i.e. the sound of the ball being kicked is used to trigger the system). Furthermore to transfer the system to cricket the smaller size of ball would require the scaling of markers or the alteration of the ball's surface to include the minimum of five colours required (Neilson, 2004).

3.2.7: HawkEye:

One system that has received a great deal of exposure in media coverage of both cricket and tennis is HawkEye (Hawkins, 2006). This is a computer-based ball tracking system that uses a minimum of three orthogonal cameras recording at 140 frames per second to capture the trajectory of the ball before and after it bounces. Mathematical algorithms are used to model and predict the complete ball trajectory. Data is continually streamed by the system and an operator is required to trigger recording as a bowler approaches the crease. The accuracy of the system has been the subject of some debate, however the manufacturer claims the system to be accurate to within 5 mm of real trajectories (Hawkins, 2006). The results of the HawkEye system are stored as comma separated variable files that are processed using one of the two bespoke analytical pieces of software: the HawkEye Virtual World program and the HawkEye Stats program. The Virtual World software is most commonly seen in media coverage, where delivery trajectories are displayed in a three dimensional representation of the playing arena. The Stats package displays the delivery data quantitatively i.e. the release speed of the ball, pitching position, where the ball passed the stumps, swing before bouncing and deviation post bounce. The visual display of each of the systems is depicted in figure 3.2.9.

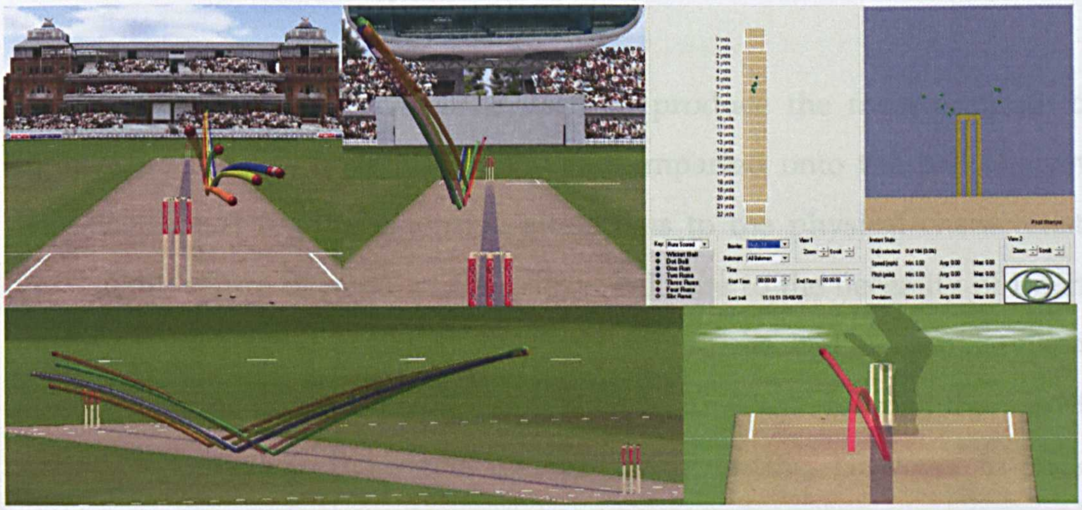
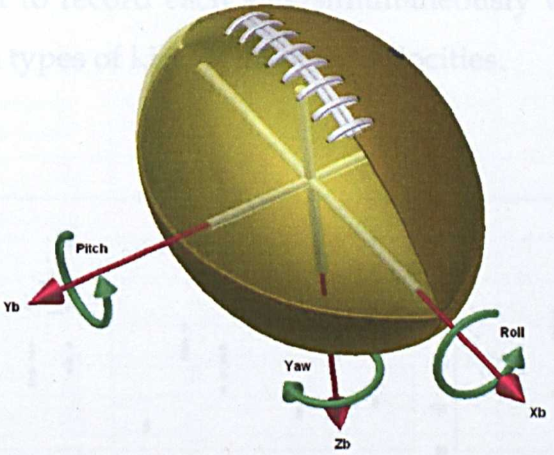


Figure 3.2.9: The HawkEye system: four different views using Virtual World software and one from Stats (top right).

3.2.8: Accelerometer:

In American football, Nowak (2003) used accelerometers housed within a 'Nerf' ball to record the flight dynamics during a number of throws. In Nowak's experiments four single axis accelerometer chips were housed inside the ball as seen in figure 3.2.10 below. The system sampled at 200 Hertz and logged and stored data for ten seconds. The system measured the axial and radial accelerations from which the wobble to spin ratio and spin rate of the ball were calculated. A spin rate of approximately 600 rpm for a standard throw was measured.



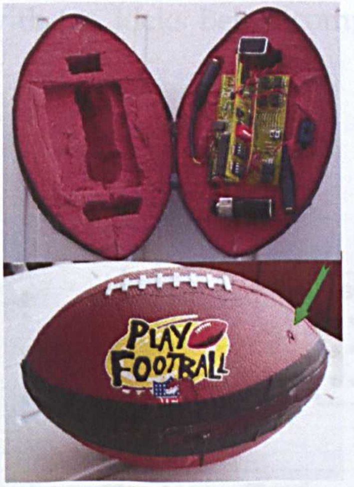


Figure 3.2.10: The setup of Nowak's accelerometer within an American football (Nowak, 2003).

Accelerometers could perhaps be used to produce the most accurate ball flight characteristics in terms of spin rate imparted onto the ball however their use would require extensive alterations to the physical characteristics (i.e. weight, centre of mass) of the cricket ball due to the necessity of internal housing (Waghray et al, 2008). In sports where the ball does not typically interact with the ground during flight such as American football there is little chance of damage to the accelerometer during testing. However in cricket, where the ball is regularly in contact with the ground and bat an accelerometer/modified ball could suffer damage during the course of testing thus making it an impractical solution for long term quantifying of cricket deliveries.

3.2.9: System Comparisons:

As detailed above there have been a number of techniques used to quantify the launch conditions of sports balls. A recent study conducted by Ronkainen et al (2008) aimed to compare three ball launch measurement systems (i.e. Quinspin, Trackman and high speed video analysis) using a soccer ball. For the experiment, a mechanical kicking simulator (Holmes et al, 2007) was used to impact the football with a straight kick and a curve kick. All three systems were set to record each kick simultaneously with ten kicks being completed for both types of kick at three leg velocities.

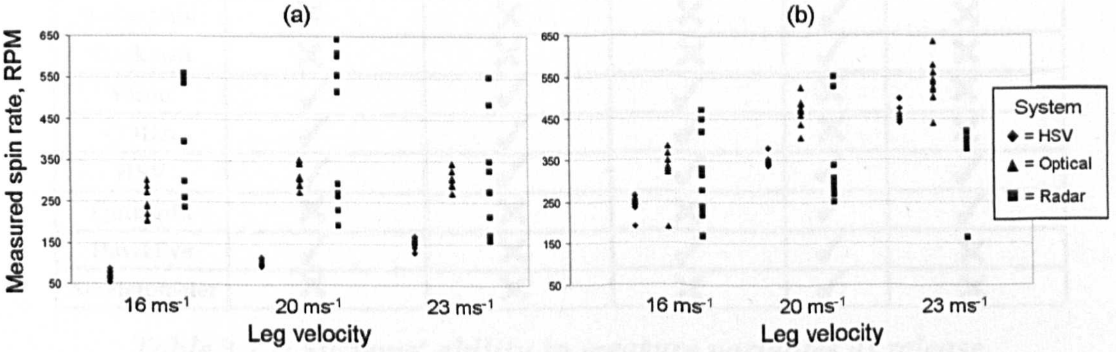


Figure 3.2.11: Spin rate measurements from three systems for straight kick (a) and curve kick (b). Adapted from Ronkainen et al (2008).

The results of the testing show that consistent data was produced *within* each of the individual systems however considerable variation was seen *between* the systems (see figure 3.2.11). The conclusions drawn from this by the investigators was that for comparison of ball flight characteristics the same system must be used throughout. Trackman (radar) appears to be the least consistent of the systems tested, for example spin measurement values between 170 and 650 rpm were recorded for the 20 ms^{-1} straight kick. High-speed video gave the most consistent measurements, never producing a spin rate spread of more than 100 rpm, however the experimental limitations of using one camera meant that spin was only determined about one axis.

<u>3.2.10: Conclusions:</u>

The analysis systems discussed above are summarised in Tables 3.2.1 and 3.2.2 and their capabilities reviewed in terms of the data they could provide to quantify cricket bowling. Within the tables, a tick represents the capability of the system to obtain the required variable, even if additional post processing is required. A cross signifies the system's inability to obtain the required variable.

	Release Position			Release Speed	Ball Orientation at Release
Analysis Systems	X (Metres Wide of Centre Stump)	Y (Metres Infront of Stumps)	Z (Metres Above Ground)	MPH	Degrees (From Normal)
Radar Gun	✗	✗	✗	✓	✗
Trackman	✗	✗	✗	✓	✗
Vicon	✓	✓	✓	✗	✗
CODA	✓	✓	✓	✗	✗
HSV	✓	✓	✓	✓	✓
Quinspin	✗	✗	✗	✓	✓
HawkEye	✓	✗	✓	✓	✗
Accelerometer	✗	✗	✗	✓	✗

Table 3.2.1: Systems' ability to measure variables at release.

	Predominant Spin Direction	Spin Rate	Launch Angle	Pitching Position	
Analysis Systems	Degrees (Normal to spin axis)	RPS	Degrees (From Horizontal)	X (Metres From Pitch Centre Line)	Y (Metres From Bowler's Stumps)
Radar Gun	✗	✗	✗	✗	✗
Trackman	✓	✓	✓	✓	✓
Vicon	✗	✗	✗	✗	✗
CODA	✗	✗	✗	✗	✗
HSV	✓	✓	✓	✓	✓
Quinspin	✓	✓	✓	✗	✗
HawkEye	✗	✗	✓	✓	✓
Accelerometer	✓	✓	✓	✗	✗

Table 3.2.2: Systems' ability to measure variables post release.

The most suitable analysis system that can be used to provide all of the required data is high-speed video. This capability is only achievable when used in conjunction with post processing software (e.g. Image Pro Plus). The Trackman system could potentially provide suitable trajectory data, however obtaining an accurate release position in 3-D space would be difficult as specifying the point at which the ball leaves the hand is not currently possible (i.e. in cricket the ball is in motion during the delivery stride prior to release as opposed to a golf shot or soccer free kick where the ball is initially stationary). Additionally, Trackman had not been used outside of golf at the time of testing commencing and the results of recent experiments conducted by Ronkainen and Holmes suggests that when measuring lower spin rates, as could be seen in cricket, other systems produce more accurate results.

Within cricket there has been little research conducted regarding the measurement of release conditions. This is particularly the case with respect to studies conducted under match conditions where, due to the nature of the game and the large playing arena, it is difficult to instrument the players or find an adequate position to house analytical equipment that does not either interfere with the game or has an appropriate resolution for accurate data sampling. Any analysis system must have minimal intrusion on the playing area of the test subjects. For this reason CODA and Vicon are not ideally suited due to the requirement of instrumenting the subjects and the positioning of secondary apparatus. In the case of Vicon, the setup necessitates analytical equipment intruding onto the non-naturally lit playing arena as illustrated in figure 3.2.12.

Figure 3.2.12: Extensive Vicon setup for player analysis.

Each of the other systems reviewed lack essential functionality when considering the requirements for the analysis of cricket bowling. A radar gun is a useful, non-invasive tool for the analysis of ball speed, however no other data are sampled. Quinspin was developed specifically for the analysis of soccer kicks and although it *could* be used to record initial flight characteristics of deliveries, the system requires the marking up of balls and is incapable of calculating release position data. An accelerometer housed inside a cricket ball could provide accurate spin data, however none of the other required variables would be determined and due to the complexity of the physical alterations required to accommodate the electronics and the likelihood of damage occurring to the accelerometer on impact with the playing surface means this option was not considered further.

HawkEye is the only option that would readily support analysis under match conditions. This is due to the system's ability to be housed at the periphery of the playing arena and still focus upon each delivery released. One issue with HawkEye is its inability to measure the level of spin imparted onto the ball. Spin is a key component of cricket deliveries and an essential variable that needs to be quantified to enable accurate evaluation of a bowling machine's ability to recreate human deliveries.

Provided that cameras can be housed with minimal intrusion to the playing area and have minimal influence over the test subjects' performance, high speed video analysis is the most suitable method of analysing cricket bowling. If three-dimensional analysis of the bowlers' positions are to be measured then a minimum of two cameras are required, ideally positioned orthogonally and focussed upon the area of ball release. Further, to capture the pitching position of each delivery it is necessary to have a third camera capturing the ball's first point of contact with the pitch. To ensure accurate measurements are taken, careful calibration of each camera is necessary with reference images taken with objects of known dimensions placed centrally and at the extremities of the field of view to counteract any errors associated with lens distortion (Symes, 2006).

3.3: Player Testing

A series of player tests were designed and conducted at an indoor training facility with the aim of quantifying: (i) the characteristics of the cricket ball as it is released and (ii) the physical position of release by the bowler. These data have been analysed focussing on the required output of the bowling machine and the batsman's requirements for the system visualisation. This section is focused upon the performance requirements of a bowling machine. The requirements of batsmen are addressed in Chapter 7 of this thesis.

The sample consisted of one spin bowling group (N=8) and one pace bowling group (N=10) of national standard bowlers. The bowlers were asked to bowl their stock delivery (the delivery that they would bowl most often in matches and are most comfortable bowling) as if to a right handed batsman, aiming to land the ball on the pitch down a typical line and at a length identified by their coach prior to testing. The players were also asked to bowl examples of any variations of delivery that they would feel comfortable bowling in a competitive match. The groups were divided into sub groups of approximately 3-4 players to avoid crowding the testing area and to reduce the waiting time between deliveries to a minimum. The players bowled single deliveries in rotation one after the other. This was followed by further rounds of deliveries until each sub group had been tested. From the testing a set of initial ball flight characteristics were determined along with the release positions within 3-D space for each ball bowled.

A test bed was designed to house two orthogonal high speed cameras focussed upon the area of ball release. One camera was located directly above the popping crease at a height of 3.40 m (High speed camera 2, figure 3.3.1). This was achieved by fixing a camera mounting plate to a 5 m beam that was supported by two heavy duty tripods located at either side of the playing surface, not obstructing the bowler. The second camera was supported by a Manfrotto tripod along the line of the popping crease at a height of 1.98 m and 2.15 m wide of centre stump (High speed camera 1, figure 3.3.1). This position was chosen as it gave the best view of the ball release and early flight of the ball. The positioning was decided using the assumption that the majority of bowlers will land with their front foot on or just behind the popping crease with release of the ball occurring approximately above the front foot for spinners and in front of the front foot for fast bowlers (Portus, 2001). These cameras recorded the bowler throughout the delivery stride and release of the ball. The early flight of the ball post release was also captured enabling the characteristics of the ball in flight to be measured.

A third high speed camera was positioned directly above a desired pitching area at a height of 3.13 m (High speed camera 3, figure 3.3.1). The purpose of this camera was to record the ball's first point of contact with the pitch post release from the bowler (pitching position). The testing session was recorded by two additional standard 50 Hz video cameras; one positioned to obtain an Umpire's viewpoint, the other was positioned to record a batsman's viewpoint (50 Hz cameras 1 and 2 respectively, figure 3.3.1). These cameras were used to provide an overview of each delivery. In addition the positioning of the cameras was also intended to provide the bowlers with a more realistic obstacles (i.e. umpire, batsman) within their field of view rather than purely running in and bowling at an isolated set of stumps. A scaled CAD representation of the test setup used in the indoor facility is provided in figure 3.3.1. The CAD model was used to calculate the size and positioning of equipment when establishing the test protocol.

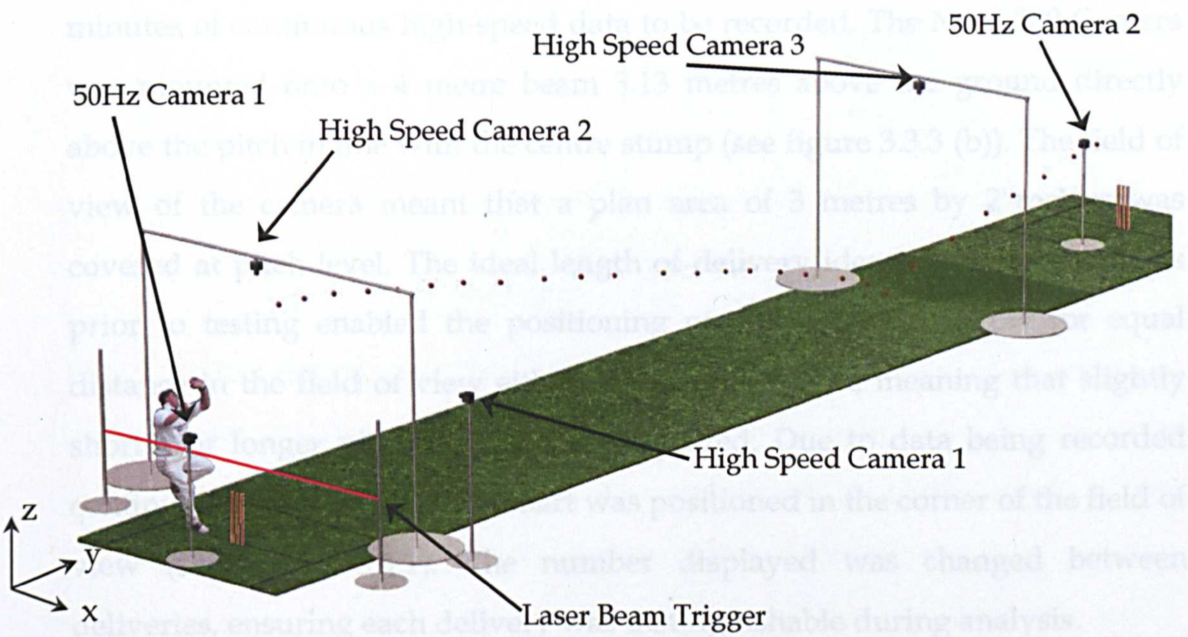


Figure 3.3.1: The setup of apparatus for indoor player testing created using CAD software.

The two Photron Ultima APX high-speed video cameras (HSC 1 and 2, figure 3.3.1), chosen to capture the bowling action and ball release characteristics of the players enabled recording at 2000 frames per second with a screen resolution of 1024 x 1024 pixels maximising the clarity within the field of view. The lens chosen for both cameras was an AF Zoom-Nikkor f/2.8-4D IF Nikon. The two systems were set to initiate recording simultaneously, enabling synchronised video playback of the bowling action from side-on and above views. To initiate the recording of data simultaneously, a laser beam trigger was set up 0.48 metres in front of the stumps during the bowler's run up. When the beam was broken during the bowler's run a 5 volt TTL trigger was sent to both cameras to initiate recording.

The third high speed camera used in the testing was a NAC 500 high-speed video system. This is an analogue system that records data onto VHS tapes. These videos were later digitised using a National Instruments image grabbing card and a PC. The system was specifically chosen because it enabled the continuous capture of data, with a 3 hour VHS tape allowing 43 minutes of continuous high-speed data to be recorded. The NAC 500 Camera was mounted onto a 4 metre beam 3.13 metres above the ground directly above the pitch in line with the centre stump (see figure 3.3.3 (b)). The field of view of the camera meant that a plan area of 3 metres by 2 metres was covered at pitch level. The ideal length of delivery identified by the coaches prior to testing enabled the positioning of the camera to allow for equal distance in the field of view either side of this length, meaning that slightly shorter or longer pitched balls were captured. Due to data being recorded continuously, a numbered flipchart was positioned in the corner of the field of view (see figure 3.4.1). The number displayed was changed between deliveries, ensuring each delivery was distinguishable during analysis.

Figure 3.3.2 is a schematic diagram displaying the setup of each camera used during testing.

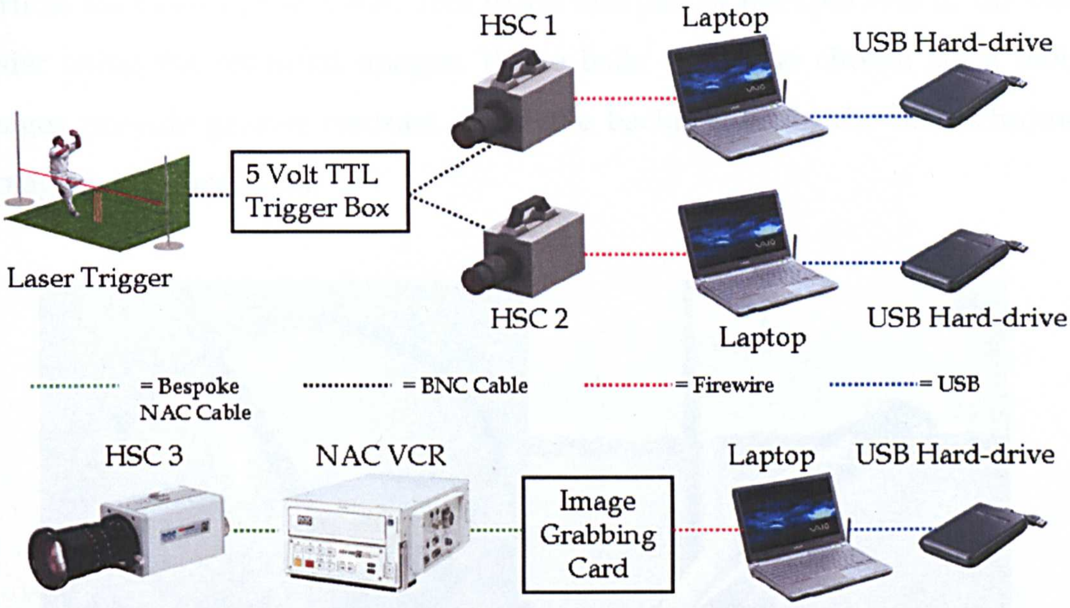


Figure 3.3.2: Schematic diagram of the high speed camera test equipment setup.

Photographs taken during the indoor testing session are displayed in figures 5.3.2. (a) and (b). The left hand picture (a) shows the high speed camera setup at the bowler's end during testing, the right picture (b) shows the NAC 500 camera setup at the batsman's end during camera calibration.

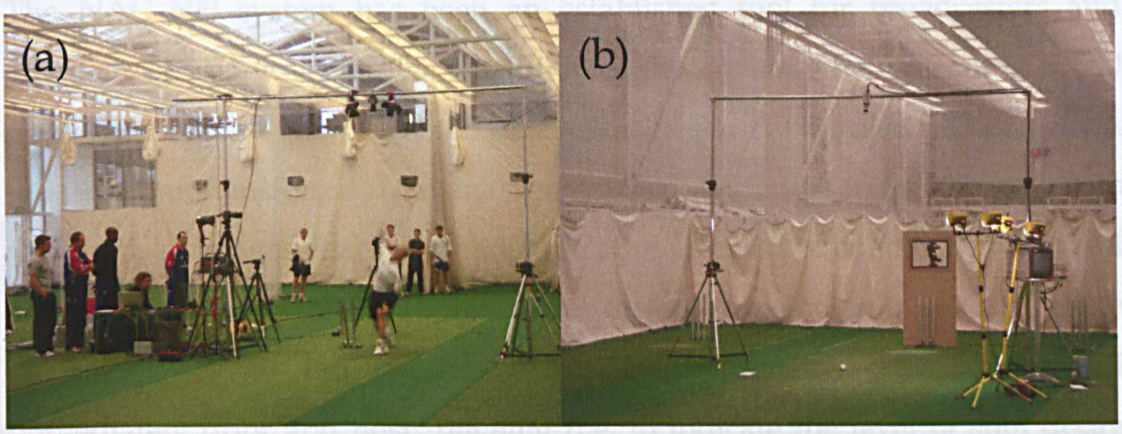


Figure 3.3.3: (a): The test set up at the bowler's end and (b): NAC 500 system hoisted above the pitching position.

Cricket balls were supplied to the players prior to testing. These balls had been pre marked with lines along the equator of the ball in the horizontal and vertical axes (see figure 3.3.4). This made analysis of the spin rate of the ball easier using the recorded images. White balls were also chosen since their images provide greater contrast above the background in the monochrome footage (see figure 3.3.4).

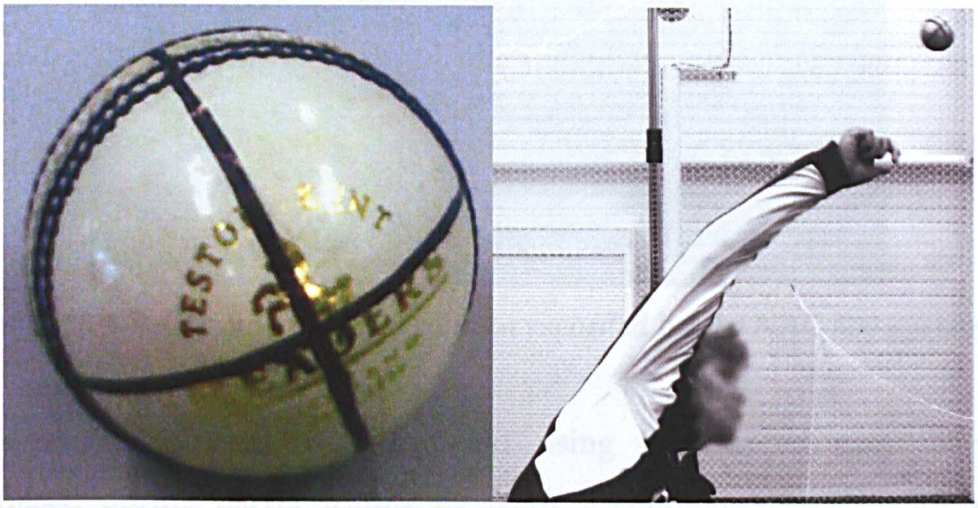


Figure 3.3.4: The markings placed upon cricket balls prior to testing (left) and a ball during testing (right).

3.4: Errors in Equipment and Setup:

The NAC 500 system has been an established tool for broadcasters and scientists for many years. The resolution of the system when sampling at 500 frames per second was 510 X 485 pixels. Image clarity was also reduced when the data was transferred from analogue to digital media format. Nevertheless the digitised images enabled the identification of point of contact between ball and pitch (see figure 3.4.1). However due to the lower quality of these recordings it was not possible to determine the spin rate of the ball immediately prior and post pitching (i.e. to indicate the level of spin decay over the flight of the ball).

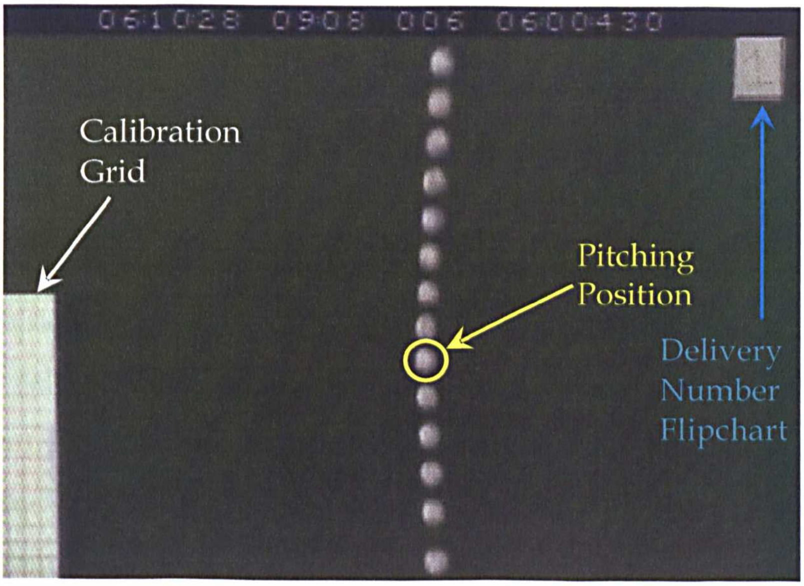


Figure 3.4.1: Composite image of data recorded by the NAC 500 system.

Errors associated with data sampled using high speed cameras were minimised during player testing by using a calibration board with a pre marked grid placed upon it with divisions of 25 mm (grey lines) and 50 mm (black lines). The board was positioned at the centre and corners of the field of view at known distances away from the cameras (see figure 3.4.2). This meant that measurements could be converted into distances in the video images by measuring the number of pixels corresponding to the known calibration distance.

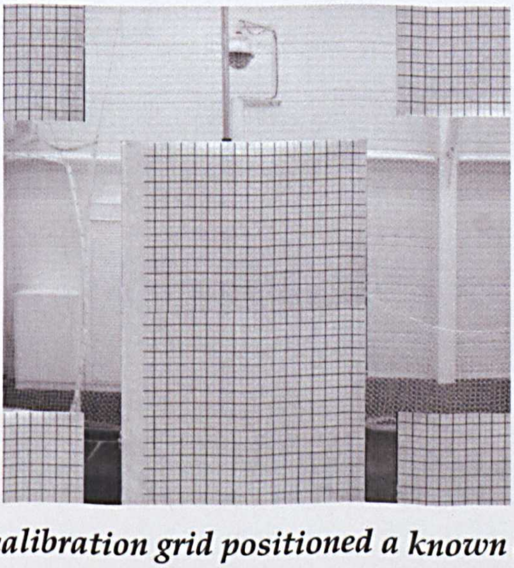


Figure 3.4.2: The calibration grid positioned a known distance from the camera lens (HSC 1, figure 3.3.1) in the centre and the corners of the field of view.

The image produced by a curved camera lens is not a pure orthographic projection of the plane of motion as there is distortion in the images resulting in differences between objects observed in the centre and edges of the field of view. This was minimised by positioning the camera as far as possible away from the players' release area whilst maintaining the clarity of picture and appropriate field of view (i.e. 2.32 m x 2.32 m). Lens distortion was further reduced by selection of a lens with a small curvature (AF Zoom-Nikkor f/2.8-4D IF Nikon). For example, for the video data recorded by high-speed camera 1 (see figure 3.3.1) 50mm in the centre of the field of view was equal to 39 pixels, meaning 1 pixel was equal to 0.00128 metres. At the extremity of the field of view 50mm was equal to 40 pixels, meaning that 1 pixel was equal to 0.00125 metres. This could equate to a 2.3% measurement error should this effect not be considered.

High-speed video footage was recorded of each bowler's delivery action. Data were recorded of each bowler from the point of rear foot impact up until the ball had exited the field of view. Typical recordings of 751 MB took approximately four minutes to transfer from the Photron high-speed cameras to PC. This severely limited the number of deliveries collected due to the limited availability of athletes and the amount of time taken waiting for data to download between deliveries.

3.5: Analysis of Results:

The first of the criteria considered was the spin rate of the ball post release from the bowler's hand (number 5 in figure 3.5.3). To do this video analysis software (Image Pro Analyser 6.2) was used to digitise the images by placing software markers upon the ball at relevant points during the ball's flight. A line was marked along the axis of the seam or the axis of one of the pre-drawn quartered markings on the ball and the frame number recorded. When the selected axis had undergone a desired level of rotation (iii, figure 3.5.1) (usually one complete revolution) the video was paused, the level of rotation was noted and the frame number recorded. A simple calculation was then required to ascertain the amount of time that had elapsed between the two frames and equate that to the level of rotation experienced by the ball in that time. As the recording rate was known (2000 frames per second) the number of frames could be used to give the elapsed time. Spin rates were then calculated as a number of revolutions per second.

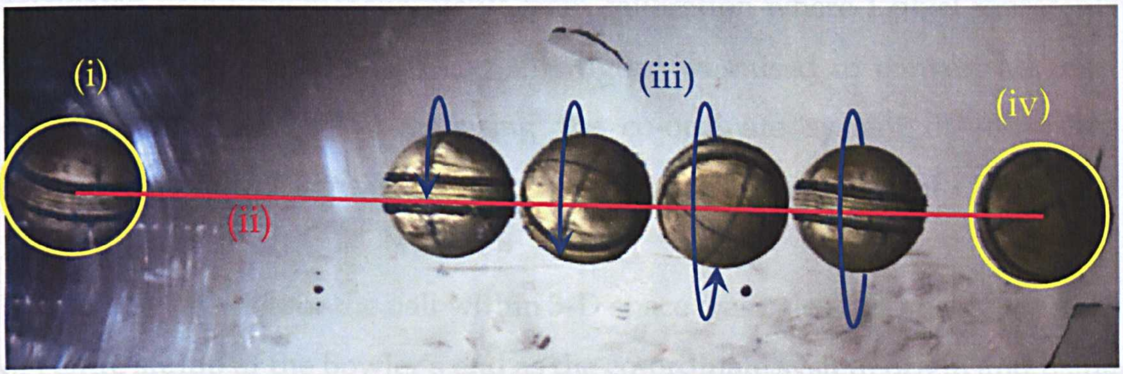


Figure 3.5.1: Analysis of ball speed and spin rate.

The two dimensional position of the ball was captured at the beginning (i, figure 3.5.1) and end (iv, figure 3.5.1) of the recorded video by placing markers around the circumference of the ball. The frame numbers of these ball positions was noted and this enabled the horizontal and vertical distances travelled to be calculated over a known time period assuming a straight line trajectory. The distance in pixels was then measured between the centres of each of the marked circles (ii, figure 3.5.1) and the physical distance calculated using the conversion factors from the calibration outlined above. The time elapsed was calculated as above and the speed of the ball determined using equation 3.5.1.

Using the approximation that the ball flight is a straight line over the measurement region, it was possible to use the following equation to the calculate the horizontal and vertical speeds:

$$v = \frac{d}{t}$$

Equation 3.5.1

Where v is the speed in the horizontal or vertical direction in m/s, d is the distance travelled in the vertical or horizontal direction in metres and t is the time taken in seconds. The resultant velocity was then calculated as the vector sum of the horizontal and vertical speed components. Distances were calculated using the measurements from calibration where 1 pixel represents 0.00128 metres in real space and this figure was used to convert all pixel distances into real distances using the co-ordinate system of the video analysis software. All measurements were taken to an accuracy of +/- 1 pixel.

The release position of the ball within 3-D space was calculated using the base of centre stump at the bowler's end as the co-ordinate system origin and using post processing software to measure the distance from the origin to the centre of the ball in the X and Y axes (see figure 3.5.2). The release position in the z axis (release height) was measured with respect to the base of the field of view (figure 3.5.2). This was a known distance from the floor, established during the calibration stage. This offset was added to the measured distance from the centre of the ball to the bottom of the field of view and converted into physical distances.

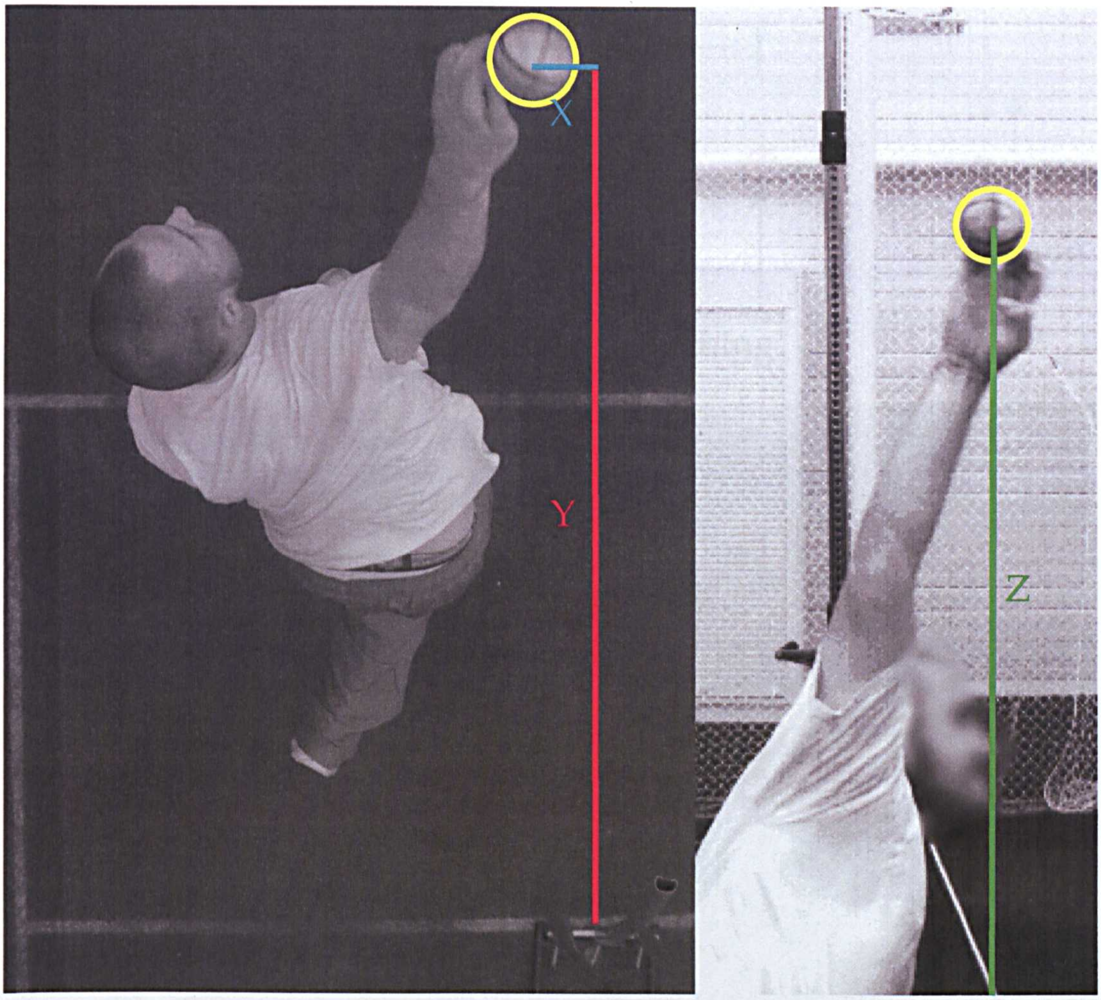


Figure 3.5.2: The measurement of release position in X, Y and Z axes. X and Y measured with respect to the base of centre stump, Z measured with respect to the bottom of the field of view, a known distance, then converted to distance from floor.

The measurements taken in order to quantify the deliveries bowled are detailed in Figure 3.5.3.

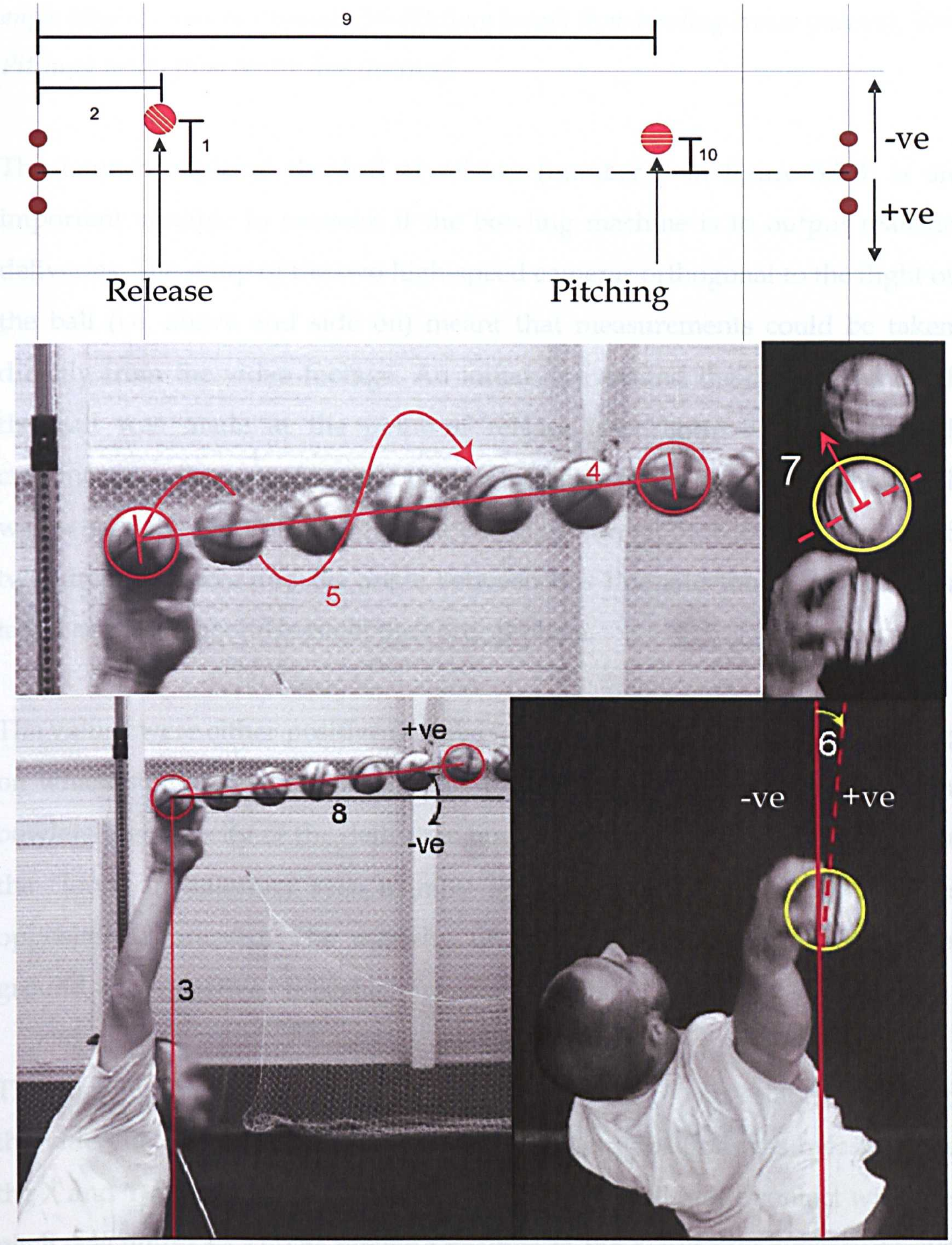


Figure 3.5.3: The calculation of variables required to quantify bowling deliveries.

Note: 1= Release position wide of centre stump (metres), 2= Release position from bowling crease (metres), 3= Release height from floor (metres), 4= Release speed (mph), 5= Ball spin rate (rps), 6= Ball orientation at release (degrees from normal), 7= Predominant spin direction (degrees normal to predominant spin axis), 8= Launch *angle (degrees from horizontal), 9= Pitching length from bowling crease (metres), 10= Pitching width from centre line (metres).*

The Launch angle of the ball at release (number 8 in figure 3.5.3) is an important variable to measure if the bowling machine is to output realistic deliveries. The setup of the two high-speed cameras orthogonal to the flight of the ball (i.e. above and side on) meant that measurements could be taken directly from the video footage. An initial line around the circumference of the ball was made at the point of release (see figure 3.5.3). A second circumference line was drawn at the last available frame where the whole ball was within the field of view. A line was then drawn between the centres of two circumferences and the angle between this line and the horizontal was taken as the angle of release in the vertical plane.

The values were either positive (i.e. above) or negative (i.e. below) depending on which side of the horizontal plane the ball was launched. Note: for spin bowlers the majority of the deliveries bowled were classed as positive due to the "loop" in trajectory seen in most spin deliveries. For fast bowlers the opposite is observed. The majority of deliveries are angled towards the ground with negative vertical launch angle values.

The pitching position of the ball (9 and 10, figure 3.5.3) was established using the video data from HSC 3 (figure 3.3.1). Pitching position was measured in the X and Y axes from the first frame in which the ball made contact with the pitch (see figure 3.4.1). The pitching position in the X axis was measured with respect to the edge of the cricket pitch. The measurement in the Y axis was taken from the top of the field of view, a known distance from the stumps at the bowler's end. Measurements were made in pixels and converted into distances using the conversion factor of 1 pixel = 0.00385 metres, established from a calibration grid positioned within the field of view (see figure 3.4.1). Measuring the orientation of the ball at release was important in order that balls are fed into the bowling machine in the correct position since the orientation of the ball and the direction in which the ball is spinning provides the batsman with visual cues pertaining to delivery type (Muller, 2006, see Chapter 2). In order to quantify the ball orientation at release, the angle of the seam was measured from the video data sampled by HSC 2 (see figure 3.3.1), the plan view of the bowling action. The point of release was identified as the first frame where no contact existed between the bowler's hand and the ball. In this frame the angle of the seam was measured with respect to the direction of motion of the ball (see number 6, figure 3.5.3). Angles were measured with positive and negative values with maximum range of 90 and -90 degrees in each direction (i.e. 0 degrees indicating that the seam is in the direction of travel).

The predominant direction of spin was quantified by tracking the rotation of points on the ball post release and representing the direction of rotation of these points using a single measurement i.e. an angle measured with respect to the direction of motion of the ball from the plan view provided by HSC 2 (figure 3.3.1). Angles were measured with positive and negative values with maximum magnitude of 180.0 and -180.0 degrees. Examples of these measurements are illustrated in figure 3.5.4.

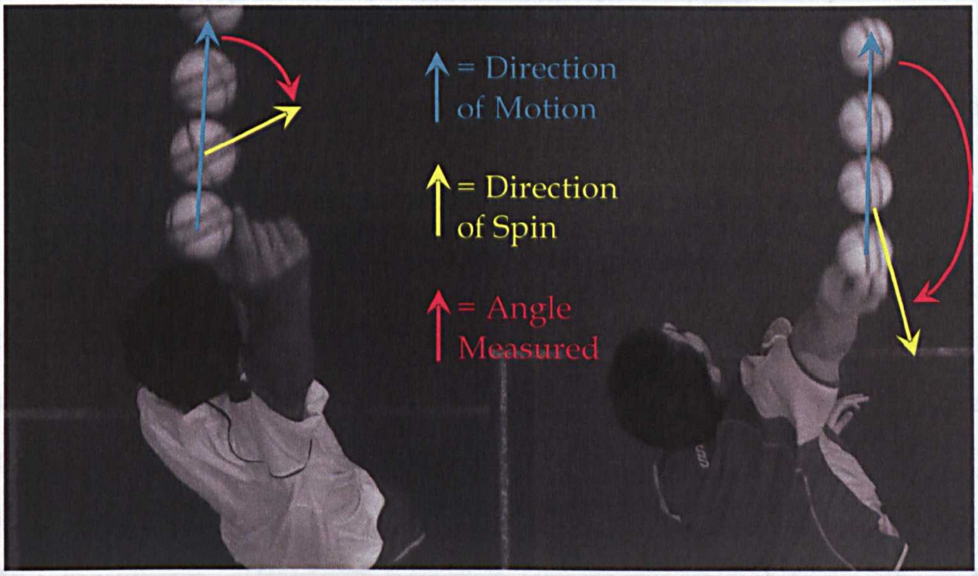


Figure 3.5.4: Measuring the predominant direction of spin.

3.6: Results:

Tables listing the full quantitative results of the bowling analysis are given in Appendix A. This section is focused upon highlighting the main characteristics of the spin and pace deliveries. The bowlers test identification number, the arm that they bowl with and the type of bowler they are classified as are summarised in Table 3.6.1.

Bowler	Arm	Bowler Type
Bowler 1	Right Arm	Leg Break
Bowler 2	Right Arm	Off Spin
Bowler 3	Right Arm	Off Spin
Bowler 4	Right Arm	Off Spin
Bowler 5	Right Arm	Off Spin
Bowler 6	Left Arm	Orthodox
Bowler 7	Left Arm	Orthodox
Bowler 8	Left Arm	Orthodox
Bowler 9	Right Arm	Pace
Bowler 10	Right Arm	Pace
Bowler 11	Right Arm	Pace
Bowler 12	Right Arm	Pace
Bowler 13	Right Arm	Pace
Bowler 14	Right Arm	Pace
Bowler 15	Right Arm	Pace
Bowler 16	Right Arm	Pace
Bowler 17	Right Arm	Pace
Bowler 18	Left Arm	Pace

Table 3.6.1: The bowlers tested, the arm they bowl with and bowler type.

3.6.1: Spin Bowlers

The mean, maximum, minimum, standard deviation, standard error in the mean and number of deliveries analysed for each of the required variables needed to recreate a right handed off spin delivery (see section 2.3.4.2) are listed in Table 3.6.2. The measurement uncertainty is also quoted. (Note: this was the maximum difference between values measured for each variable when the same variable was measured ten times on ten different occasions).

Right Arm Off Spin	Release Position X	Release Position Y	Release Position Z	Speed	Spin Rate	Ball Orientation at Release	Predominant Spin Direction	Launch Angle	Pitching Length	Pitching Width
N=12	(metres wide of centre stump)	(metres from bowler's stumps)	(metres from floor)	(mph)	(rps)	(degrees from normal)	(degrees normal to spin axis)	(degrees from horizontal)	(metres from bowler's stumps)	(metres wide of centre stump)
Measurement Uncertainty	±0.0121	±0.0152	±0.0074	±0.672	±0.800	±0.90	±1.12	±0.40	±0.0116	±0.0077
Mean	-1.033	1.061	2.246	41.85	27.70	53.0	44.9	4.0	16.301	-0.613
Max	-0.460	1.287	2.376	45.23	36.80	85.0	74.0	7.1	17.220	-0.276
Min	-1.952	0.736	2.170	39.82	19.12	26.0	26.0	-1.9	14.520	-0.919
S.D.	0.4886	0.1671	0.0694	1.543	5.265	16.76	13.32	2.75	0.8834	0.2209
Standard Error	0.1472	0.0503	0.0209	0.465	1.586	5.05	4.01	0.83	0.2661	0.0665

Table 3.6.2: Variables measured from the deliveries of right arm off spin bowlers.

The largest positional variation is seen in the release position in the X direction with the difference between the most narrow and widest release positions being 1.492 metres. This is a significant distance when considering that the width of a cricket pitch is 1.32 metres from centre stump to the edge of the pitch. The widest of the deliveries was released from outside the confines of the pitch (1.952 metres from centre stump). There is a high standard deviation seen in the ball orientation at release for the right handed off spin bowlers. A range of 59 degrees was seen between the smallest (26 degrees) and largest (85 degrees) angles relative to the ball's direction of motion. This variation can be attributed to varying techniques exhibited by individual bowlers. The data presented in Appendix A indicates the largest standard deviation for ball orientation is 21.9 degrees (bowler 5). However the next largest is 7.8 degrees (bowler 1) suggesting that this is, in general, a controlled element of the bowling action and that bowlers will vary the orientation of the ball individually. It is not surprising to note that the flattest delivery bowled (-1.9 degrees) was also the shortest in pitching length, bowled by bowler 3 (see Appendix A).

The left arm orthodox delivery is identical in technique to the right arm off spin delivered by left arm bowlers. The left arm bowlers released the ball from around the wicket throughout testing (i.e. all bowlers released from the same side of the stumps). The results are presented in Table 3.6.3. There was considerably less variation in the release width (σm = 0.1137 metres) and greater variation in release length (0.3079 metres) for the left arm bowlers than seen in the right arm off spinners (0.4886 metres and 0.1671 metres respectively) (see Tables 3.6.2 and 3.6.3.) The predominant direction of spin is closer to the direction of motion (-30.4 degrees) than seen in the off spin delivery (44.9 degrees), (see figure 3.6.1 below).

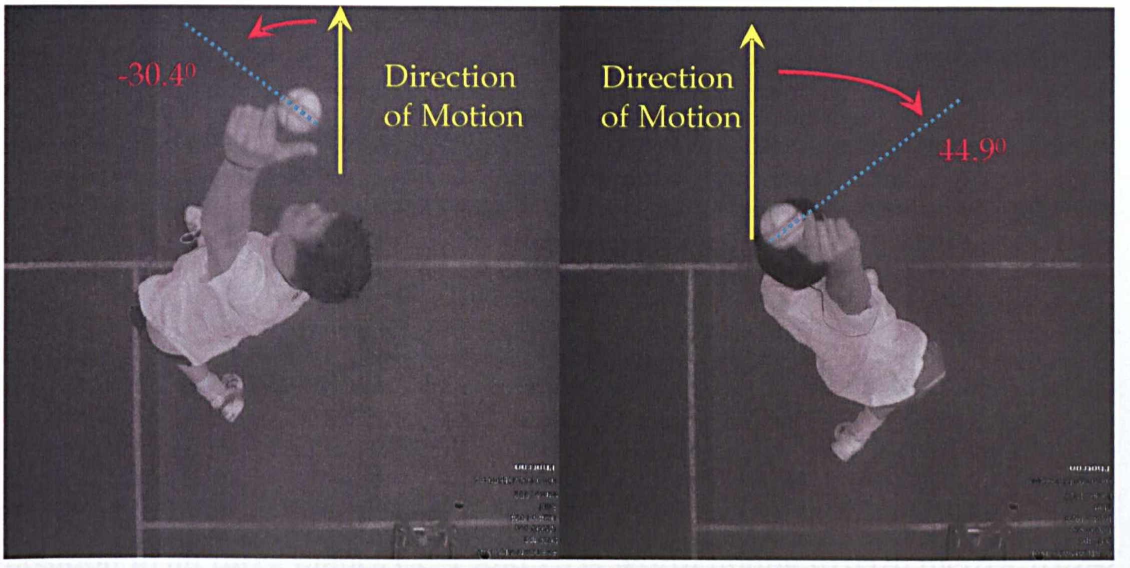


Figure 3.6.1: The ball orientation at release, from a left arm orthodox bowler (left) and a right arm off spinner (right).

Although pre-testing it was anticipated that the ball would be released with a negative spin direction, the lower angle indicates that the ball was released with a greater component of top spin as opposed to rifle spin. It should be noted that the release speeds of both the right arm off spin bowlers and the left arm orthodox bowlers are similar, ranging from 39.10 mph to 45.85 mph (see figure 3.6.3) with standard deviation figures of 1.543 mph and 2.073 mph for right and left handers respectively. The spin rate of the left arm bowlers (23.50 rps) was lower than that recorded from the right arm bowlers (27.70 rps). There is no clear reason for this, however it can be attributed to variation seen in the spin imparting actions adopted by different bowlers (see section 2.3, Chapter 2).

Left Arm Orthodox	Release Position X	Release Position Y	Release Position Z	Speed	Spin Rate	Ball Orientation at Release	Predominant Spin Direction	Launch Angle	Pitching Length	Pitching Width
N=9	(metres wide of centre stump)	(metres from bowler's stumps)	(metres from floor)	(mph)	(rps)	(degrees from normal)	(degrees normal to spin axis)	(degrees from horizontal)	(metres from bowler's stumps)	(metres wide of centre stump)
Measurement Uncertainty	±0.0121	±0.0152	±0.0074	±0.672	±0.800	±0.90	±1.12	±0.40	±0.0116	±0.0077
Mean	-0.731	0.853	2.168	42.09	23.50	-44.8	-30.4	4.2	15.660	-0.362
Max	-0.563	1.190	2.281	45.75	28.56	-40.0	-12.0	9.7	16.755	-0.091
Min	-0.888	0.362	2.052	39.10	15.84	-51.0	-45.0	-0.9	14.236	-0.576
S.D.	0.1137	0.3079	0.0901	2.073	4.745	4.49	12.08	3.56	0.8845	0.1621
Standard Error	0.0402	0.1088	0.0319	0.732	1.677	1.59	4.27	1.26	0.3125	0.0573

Table 3.6.3: Variables measured from the deliveries of left arm orthodox bowlers.

The results of right arm leg spin deliveries bowled during the test session are presented in Table 3.6.4. Although these appear to be the most consistent of the deliveries bowled with comparatively low standard deviation values seen for each of the variables this is attributed to the small sample size (2 deliveries) available rather than the consistency of the bowler in question. The small sample size was the result of constraints on time during testing and the lack of high quality leg spin bowlers available. The small variation in release position in all three planes (X, Y and Z) is worth noting (0.0570 metres, 0.0247 metres and 0.0018 metres respectively).

Right Arm Leg Break	Release Position X	Release Position Y	Release Position Z	Speed	Spin Rate	Ball Orientation at Release	Predominant Spin Direction	Launch Angle	Pitching Length	Pitching Width
N=2	(metres wide of centre stump)	(metres from bowler's stumps)	(metres from floor)	(mph)	(rps)	(degrees from normal)	(degrees normal to spin axis)	(degrees from horizontal)	(metres from bowler's stumps)	(metres wide of centre stump)
Measurement Uncertainty	±0.0121	±0.0152	±0.0074	±0.672	±0.800	±0.90	±1.12	±0.40	±0.0116	±0.0077
Mean	-0.824	1.206	2.079	42.74	26.17	-35.5	-31.0	6.4	16.747	-0.270
Max	-0.783	1.224	2.080	43.98	26.32	-30.0	-30.0	7.3	17.320	-0.233
Min	-0.864	1.189	2.078	41.50	26.01	-41.0	-32.0	5.5	16.174	-0.306
S.D.	0.0570	0.0247	0.0018	1.754	0.219	7.78	1.41	1.21	0.8107	0.0517
Standard Error	0.0570	0.0247	0.0018	1.754	0.219	7.78	1.41	1.21	0.8107	0.0517

Table 3.6.4: Variables measured from the leg spin deliveries of a wrist spin bowler.

The bowler in question bowled a sample of delivery variations during the testing session. These were the standard leg break delivery, slider, flipper and googly. The release technique and resulting mean predominant spin direction imparted onto the ball for each of these deliveries is summarised below in figure 3.6.2:

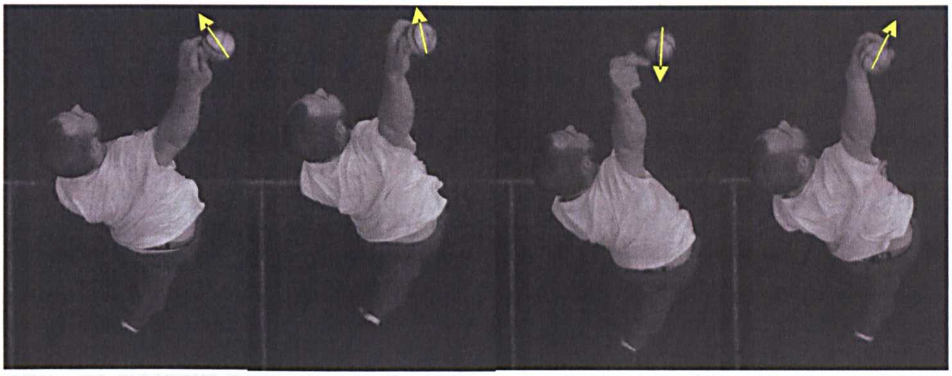


Figure 3.6.2: The four wrist spin variations seen during testing with arrows representing the predominant direction of spin imparted for each: (from left to right); leg break, slider, flipper and googly.

There were two leg break deliveries bowled and one example each of the other three variations. For these three variations the data displayed in Table 3.6.5 are taken from the single examples available and hence on the measurement uncertainty is quoted. However for the leg break deliveries, mean values are quoted. The data are still of value in giving an indication of the delivery characteristics and providing a basis for further testing given that the deliveries were bowled by a professional with international honours.

Right Arm Leg Spin Bowler	Release Position X	Release Position Y	Release Position Z	Speed	Spin Rate	Ball Orientation at Release	Predominant Spin Direction	Launch Angle	Pitching Length	Pitching Width
N=5	(metres wide of centre stump)	(metres from bowler's stumps)	(metres from floor)	(mph)	(rps)	(degrees from normal)	(degrees normal to spin axis)	(degrees from horizontal)	(metres from bowler's stumps)	(metres wide of centre stump)
Measurement Uncertainty	±0.0121	±0.0152	±0.0074	±0.672	±0.800	±0.90	±1.12	±0.40	±0.0116	±0.0077
Leg Break (2)	-0.824	1.206	2.079	42.74	26.2	-35.5	-31.0	6.4	16.747	-0.270
Slider	-0.619	1.123	2.062	40.27	25.0	-31.0	-7.0	6.3	15.750	-0.256
Flipper	-0.818	1.184	2.027	46.47	19.3	-79.0	-175.0	1.8	18.320	-0.187
Googly	-0.853	1.152	2.016	40.36	31.3	-49.0	31.0	4.2	14.410	-0.217

Table 3.6.5: The delivery variables for each of the wrist spin variations seen.

The slider delivery is released from nearer to the stumps than any of the other deliveries recorded (i.e. -0.62 m compared to approximately -0.83 m). The leg break, flipper and googly deliveries were all released within 35 mm of each other, while the slider was released 199 mm nearer the stumps than the next nearest delivery, the flipper. The slider delivery is often bowled with the intent of striking the batsman's pads, looking for an lbw decision. This is achieved by adopting a similar action to a leg break delivery but releasing the ball with a greater component of topspin by altering the angle of the wrist. The ball continues down a straighter path than anticipated by the batsman who plays for a wider delivery and is struck on the pad. It is therefore desirable for the bowler to release the slider from nearer the stumps increasing the likelihood of the ball pitching in line with the stumps and thus the chance of claiming an lbw decision.

Of all the delivery variations, the flipper delivery is perhaps the most distinct. The ball is released with a visually different action. The bowler holds the ball between the first two fingers and thumb and squeezes the ball out by "snapping" the fingers together to impart backspin onto the ball. It is also launched at a lower vertical launch angle, in this case 1.8 degrees above the horizontal plane, and at a faster speed (4 mph faster than a leg break delivery, the next quickest seen). Additionally, the pitching length of the flipper is fuller than any of the other deliveries, specifically 18.32 metres from the bowler's stumps in this case.

The spin bowlers release speeds for their "stock" delivery are presented in figure 3.6.3. Mean values are plotted with the error bars representing the standard error in the mean for each of the bowlers. Additionally the mean release speed for all of the spin bowlers tested (42.38 mph) is represented by a black horizontal line and two dashed green lines represent one standard deviation (+/- 2.510 mph) either side of the mean.

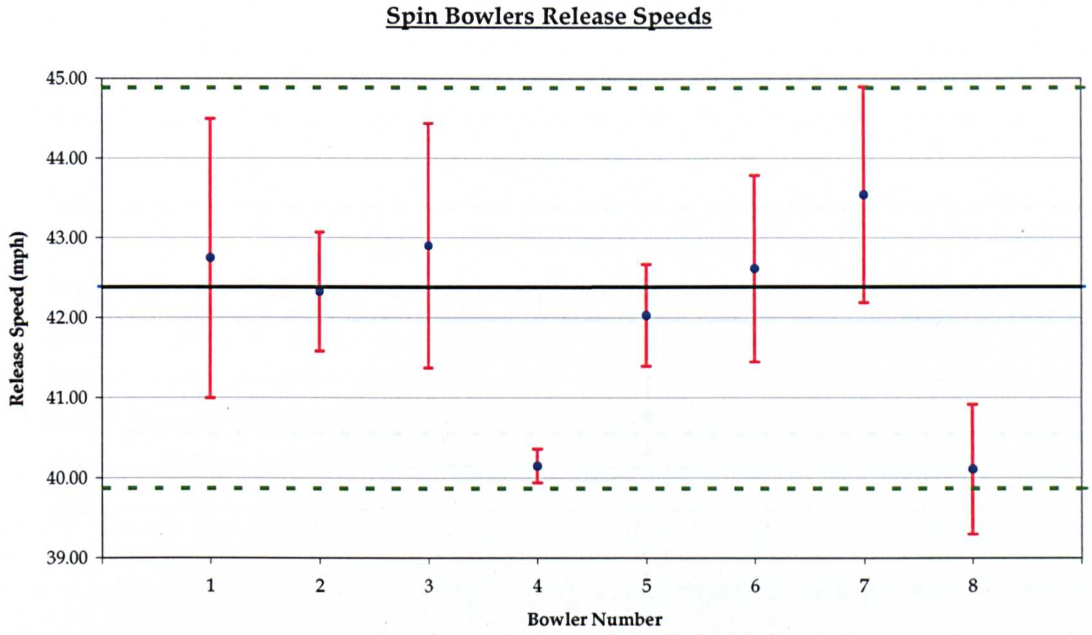


Figure 3.6.3: The resultant release speed values for each of the spin bowlers' stock delivery. Mean values are plotted with error bars representing the standard error in the mean.

The data presented in figure 3.6.3 show that of all the spin bowlers tested, only bowler 8 released any deliveries significantly different (i.e. greater than one standard deviation away from the mean) in release speed to the rest of the group. Bowler 4 was the most consistent of the bowlers tested with a standard error in the mean value of 0.208 mph. Bowler 1 was the least consistent in terms of release speed (1.754 mph standard error in the mean), however as previously discussed, this could be attributed to the smaller sample of deliveries available for analysis.

The spin rates imparted by the spin bowlers have been quantified and are presented in figure 3.6.4. Two bowlers produced significantly different (i.e. greater than one standard deviation away from the mean) results to the rest of the group. Bowler 3 imparted significantly *more* spin and bowler 8 imparted significantly *less* spin onto the ball than the rest of the group.

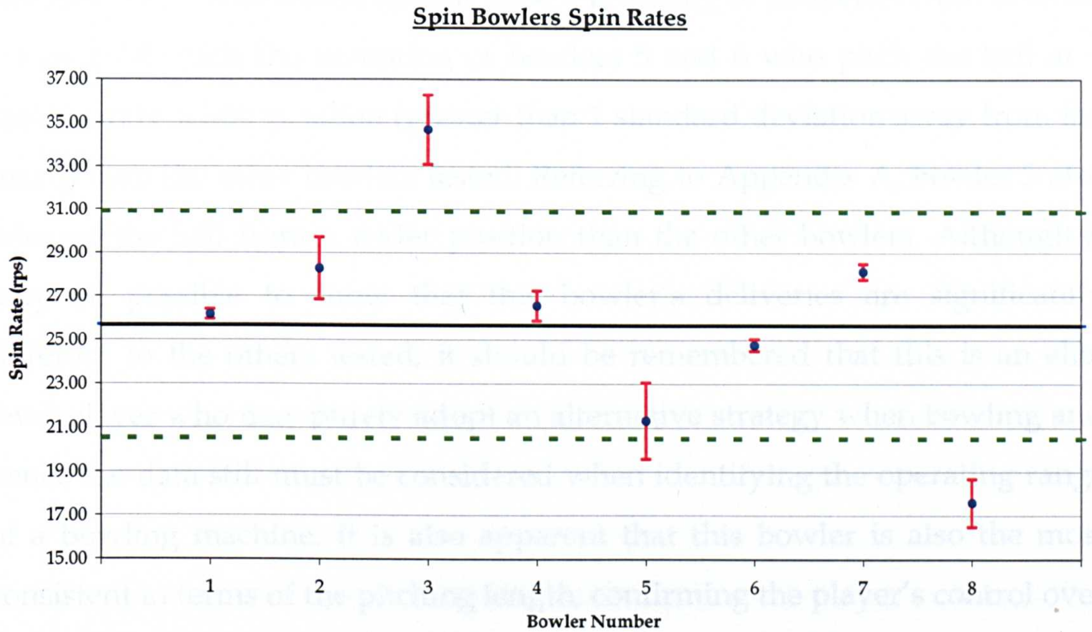


Figure 3.6.4: The ball spin rates for each of the spin bowlers' stock delivery. Mean values are plotted with error bars representing the standard error in the mean.

The consistency of the level of spin imparted onto the ball is evident from the data displayed in figure 3.6.4 with small error bars seen for all bowlers (maximum standard error in the mean value = 1.75 rps). Bowlers 1, 6 and 7 displayed a very high level of control over the level of spin imparted onto the ball with standard error in the mean values of 0.22, 0.26 and 0.35 rps respectively.

Figure 3.6.5 is a section taken from a pitch map displaying the spread of pitching positions seen for each of the spin bowlers tested. The mean pitching position is plotted with error bars representing the standard error in the mean values. Additionally the mean pitching position for all spin deliveries bowled during testing is plotted and a dashed green ring represents one standard deviation away from the mean. The zero value on the X-axis represents the centre line of the pitch. It can be seen that all of the bowlers pitched their deliveries on the offside of the pitch regardless of the spin direction imparted onto the ball. There would appear to be a grouping of deliveries from bowlers 1-4 and 7-8, with the exception of bowlers 5 and 6 who pitch the ball at a significantly wider position (greater than 1 standard deviation away from the mean) than the other bowlers tested. Referring to Appendix A, bowler 5 also releases the ball from a wider position than the other bowlers. Although it may be possible to show that this bowler's deliveries are significantly different to the others tested, it should be remembered that this is an elite level player who may purely adopt an alternative strategy when bowling and hence the data still must be considered when identifying the operating range of a bowling machine. It is also apparent that this bowler is also the most consistent in terms of the pitching length, confirming the player's control over the deliveries released.

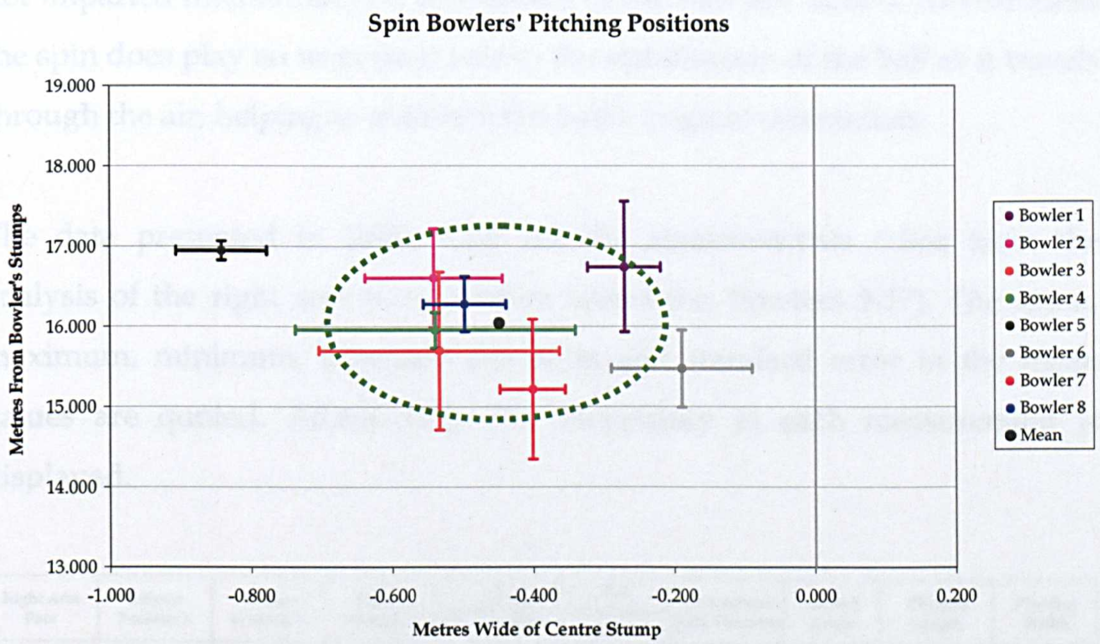


Figure 3.6.5: The mean pitching positions of the spin bowlers tested. Error bars on each of the data points represent the standard error in the mean values plotted.

Pace Bowlers:

The values measured for each of the required variables for the right and left handed pace bowlers tested (see Table 3.6.1) are presented in Tables 3.6.6 and 3.6.7 respectively. There is far less variation seen in the release width of the pace bowlers to that seen in the spin bowlers. The release speeds (78.39 mph – 60.10 mph) are quicker than those seen from spin bowlers (39.10 mph - 45.75 mph) and there are also lower spin rates observed (12.78 rps and 7.78 rps average for right and left arm pace bowlers respectively vs. 27.70 rps and 23.50 rps for right arm off spin and left arm orthodox bowlers respectively). There is still however a significant amount of spin imparted onto the ball by the pace bowlers that is almost entirely back spin (i.e. ≈ 180 degrees) imparted by the "flicking" of the first two fingers at the point of ball release. The spin is not imparted intentionally; it is resultant of the bowlers' action. Nevertheless the spin does play an important role in the stabilisation of the ball as it travels through the air, helping to maintain the ball's original orientation.

The data presented in Table 3.6.6 are the measurements taken from the analysis of the right arm pace bowlers tested (i.e. bowlers 9-17). The mean, maximum, minimum, standard deviation and standard error in the mean values are quoted. Additionally the uncertainty in each measurement is displayed.

Right Arm Pace	Release Position X	Release Position Y	Release Position Z	Speed	Spin Rate	Ball Orientation at Release	Predominant Spin Direction	Launch Angle	Pitching Length	Pitching Width
N=42	(metres wide of centre stump)	(metres from bowler's stumps)	(metres from floor)	(mph)	(rps)	(degrees from normal)	(degrees normal to spin axis)	(degrees from horizontal)	(metres from bowler's stumps)	(metres wide of centre stump)
Measurement Uncertainty	±0.0121	±0.0152	±0.0074	±0.672	±0.800	±0.90	±1.12	±0.40	±0.0116	±0.0077
Mean	-0.745	1.264	2.064	72.39	12.78	-5.9	175.6	-7.6	14.780	-0.333
Max	-0.242	1.790	2.224	77.40	25.04	10.0	180.0	-2.6	20.120	0.748
Min	-1.081	0.541	1.972	60.13	1.82	-55.0	-179.0	-19.2	12.936	-0.968
S.D.	0.2529	0.2740	0.0601	3.977	5.448	13.41	9.65	3.56	1.7607	0.3071
Standard Error	0.0395	0.0428	0.0094	0.621	0.851	2.10	1.51	0.56	0.2751	0.0480

Table 3.6.6: Variables measured of the deliveries released by right arm pace bowlers.

There is a high variation seen in release speed for right arm pace bowlers (s.d. of 3.977 mph) when compared to the spin bowlers and the left arm pace bowler. Release speeds range from 60.13 mph to 77.40 mph, which is the greatest range of any of the groups tested. The spin rate imparted onto the ball is also highly variable with a standard deviation of 5.448 rps measured. Spin rate imparted for pace bowlers would appear to be related to individual technique. The full results of each delivery bowled during testing, listed in Appendix A confirm this statement with some bowlers displaying control over the spin imparted, notably bowlers 10 and 16 whose standard deviations for spin rate are 1.73 rps and 2.17 rps respectively. On the contrary, bowlers 15 and 18 have the least control over the spin imparted with standard deviations of 5.80 rps and 5.78 rps respectively. The direction of the spin imparted confirms that pace bowlers impart backspin onto the ball (mean spin direction 175.6 degrees). Interestingly for bowler 9 there is also a component of rifle spin seen on 4 of the 6 deliveries bowled (see Appendix A) where predominant direction of spin values of 132, 155, 138 and 139 degrees are seen.

The mean, maximum, minimum, standard deviation and standard error in the mean values for the three deliveries bowled by the sole left arm pace bowler in the group are displayed in Table 3.6.7. This bowler was the fastest tested with a maximum release speed of 78.39 mph.

Left Arm Pace	Release Position X	Release Position Y	Release Position Z	Speed	Spin Rate	Ball Orientation at Release	Predominant Spin Direction	Launch Angle	Pitching Length	Pitching Width
N=3	(metres wide of centre stump)	(metres from bowler's stumps)	(metres from floor)	(mph)	(rps)	(degrees from normal)	(degrees normal to spin axis)	(degrees from horizontal)	(metres from bowler's stumps)	(metres wide of centre stump)
Measurement Uncertainty	±0.0121	±0.0152	±0.0074	±0.672	±0.800	±0.90	±1.12	±0.40	±0.0116	±0.0077
Mean	-0.944	1.483	2.027	77.07	7.23	-3.0	-177.9	-7.8	14.915	-0.234
Max	-0.926	1.561	2.059	78.39	13.56	-2.0	180.0	-5.0	16.689	-0.112
Min	-0.955	1.394	1.996	74.73	2.22	-4.0	-177.0	-12.1	13.171	-0.299
S.D.	0.0155	0.0841	0.0314	2.030	5.784	1.00	2.08	3.72	1.7592	0.1057
Standard Error	0.0110	0.0596	0.0222	1.439	4.102	0.71	1.48	2.64	1.2476	0.0750

Table 3.6.7: Variables measured of the deliveries released by a left arm pace bowler.

These data show the bowler to have a high level of control over the ball orientation at release with a range of 2 degrees between the maximum and minimum seam angles. Additionally the direction of spin imparted onto the ball is consistent (178-180°) with a standard deviation of 2.08 degrees. Consistency shown in these two variables suggests the bowler has a repeatable technique, particularly with respect to wrist and hand position when releasing the ball.

The data displayed in figure 3.6.7 are the release speeds of all the pace bowlers tested. Mean figures are plotted with error bars representing standard error in the mean values. The mean release speed of all deliveries bowled by pace bowlers (72.08 mph) is represented by a black horizontal line and one standard deviation either side of the mean (+/- 4.092 mph) is represented by green dashed lines.

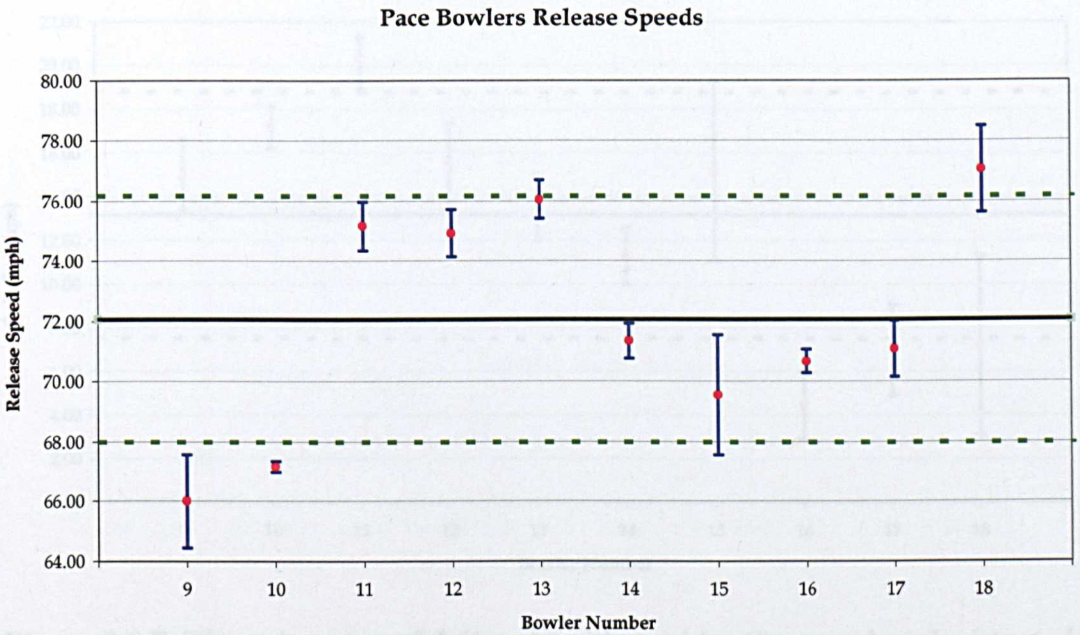


Figure 3.6.6: The release speeds of deliveries released by the pace bowlers tested.

Each of the pace bowlers tested are classified as fast-medium according to Abernethy (1981) as all of the deliveries bowled fall between 60 mph and 80 mph. Bowlers 9 and 10 produce significantly slower deliveries than the rest of the group (i.e. greater than one standard deviation away from the mean). Bowler 18 releases the ball significantly faster than the rest of the group. Bowler 10 shows a high level of control over the release speed of deliveries demonstrated by small error bars, see figure 3.6.6 (standard error = 0.178 mph).

The spin rates imparted by the pace bowlers tested are displayed in figure 3.6.7. Mean values are plotted with error bars representing standard error in the mean values. The mean spin rate for all deliveries bowled by pace bowlers is represented by the horizontal black line (13.15 rps) and one standard deviation either side of the mean is represented by dashed green lines (+/ 5.633 rps).

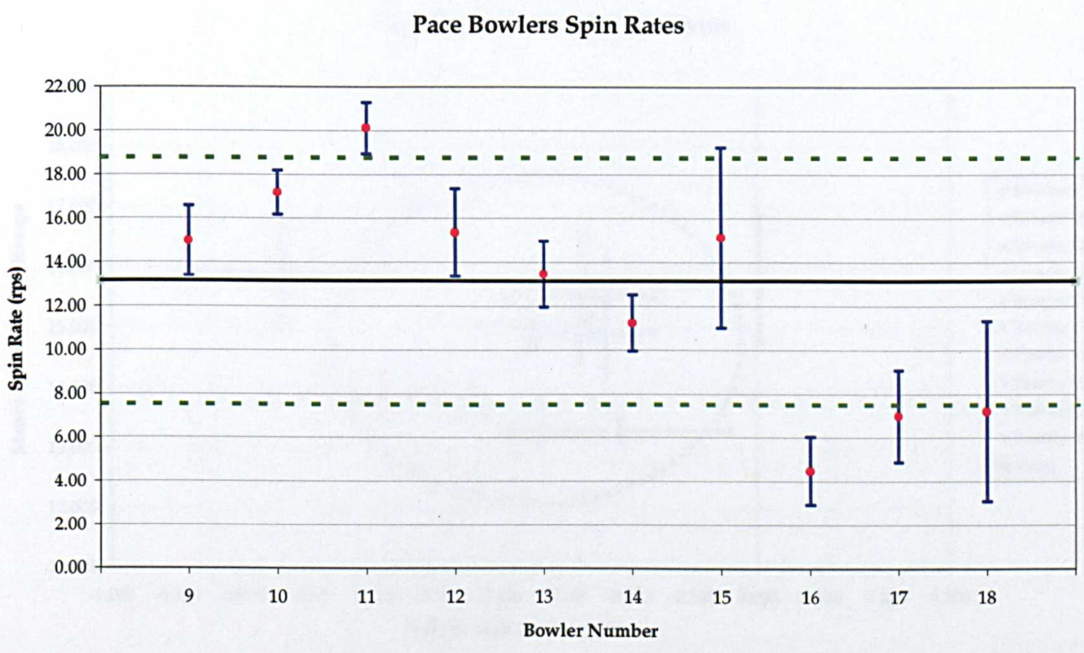


Figure 3.6.7: The spin rates of deliveries released by the pace bowlers tested.

Bowler 11 imparts a significantly greater amount of spin (i.e. greater than one standard deviation away from the mean) than the rest of the group (bowler 11 mean spin rate = 20.12 rps). Bowlers 16, 17 and 18 impart a significantly lower amount of spin onto the ball than the rest of the group with mean spin rates of

4.51, 7.01 and 7.23 rps respectively. Bowler 10 imparted the second highest level of spin witnessed during testing (mean = 17.17 rps), he was however the second slowest of the bowlers in terms of release speed (mean = 67.157 mph), suggesting that the level of spin imparted is not proportional to the release speed of the bowler and is more dependent on the technique exhibited by the individual bowler.

Figure 3.6.8 is a pitch map displaying the mean pitching positions and spread of deliveries bowled by the pace bowlers tested. Mean values are plotted with error bars representing standard error in the mean values. Additionally the mean pitching position for all pace deliveries bowled is plotted with a green dashed ring representing one standard deviation away from the mean. The zero value on the X-axis represents the centre line of the pitch.

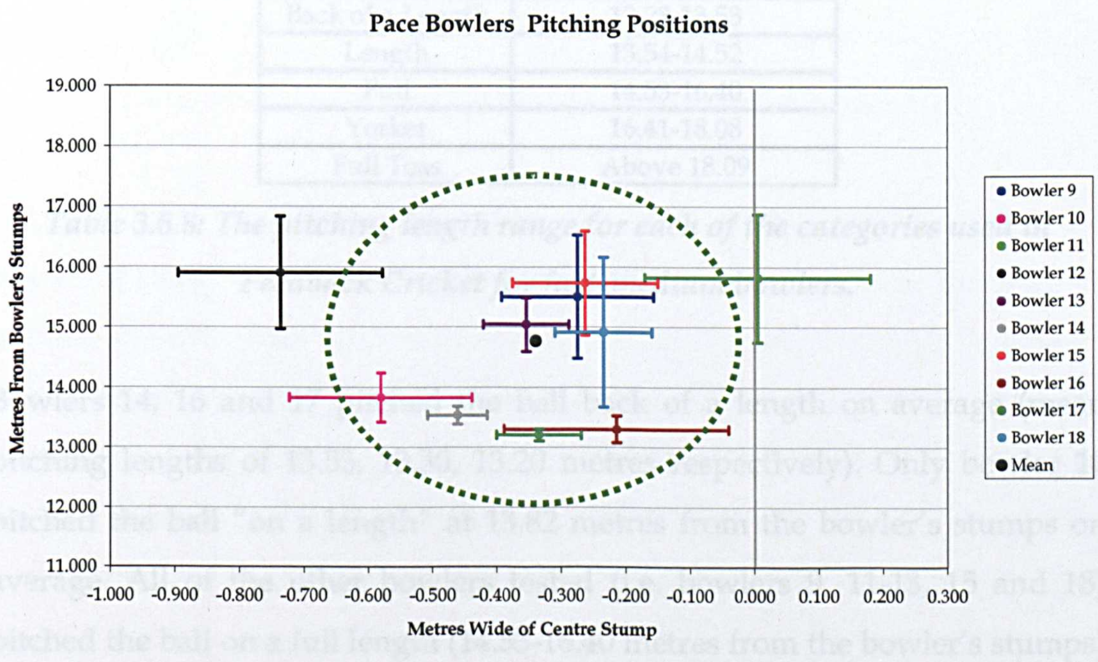


Figure 3.6.8: The mean pitching positions of the pace bowlers tested. Error bars represent the standard error in the mean values.

Bowlers 11 and 12 pitched the ball significantly wider than the rest of the group (i.e. greater than one standard deviation away from the mean). Bowler

11 pitched the ball wider on the leg side of the group mean, while bowler 12 pitched the ball wider on the off side.

As previously stated, each of the pace bowlers tested were classed as fast-medium (see figure 3.6.6). The data presented in Table 3.6.8 are the range of delivery lengths for the seven delivery length classifications available to analysts when using Feedback Cricket software (see figures 4.1.5 and 4.1.6). The figures quoted are adapted from Justham's analysis (2007) of pitching length classification, reviewed in greater depth in Chapter 4.

Delivery Length Classification	Pitching Length (metres from bowler's stumps) (+/-0.005m)
Bouncer	Up to 10.08
Short	10.09-12.17
Back of a Length	12.28-13.53
Length	13.54-14.52
Full	14.53-16.40
Yorker	16.41-18.08
Full Toss	Above 18.09

Table 3.6.8: The pitching length range for each of the categories used in Feedback Cricket for fast-medium bowlers.

Bowlers 14, 16 and 17 pitched the ball back of a length on average (mean pitching lengths of 13.53, 13.30, 13.20 metres respectively). Only bowler 10 pitched the ball "on a length" at 13.82 metres from the bowler's stumps on average. All of the other bowlers tested (i.e. bowlers 9, 11-13, 15 and 18) pitched the ball on a full length (14.53-16.40 metres from the bowler's stumps) on average. This is perhaps reflective of modern bowling styles where bowlers will often adopt one of two tactics, either to release the ball at a steeper downward angle, pitching the ball at a shorter length with the intention of the ball reaching the batsman at upper torso or head height (i.e. bowlers 14, 16 and 17). Other bowlers choose to pitch the ball at a "fuller" less aggressive length giving the ball maximum chance to swing (see Chapter 2) or laterally deviate post contact with the pitch later in the delivery (i.e. bowlers 9, 11-13, 15 and 18).

All of the data measured during testing for both spin and pace bowlers are summarised in Table 3.6.9. The objective of combining the two sets of data was to establish the operating range a bowling machine must perform if it is to replicate the level of human performance seen during testing. The mean, maximum, minimum, standard deviation and standard error in the mean values are displayed and the uncertainty in each measurement is also quoted.

All Deliveries	Release Position X	Release Position Y	Release Position Z	Speed	Spin Rate	Ball Orientation at Release	Predominant Spin Direction	Launch Angle	Pitching Length	Pitching Width
N=71	(metres wide of centre stump)	(metres from bowler's stumps)	(metres from floor)	(mph)	(rps)	(degrees from normal)	(degrees normal to spin axis)	(degrees from horizontal)	(metres from bowler's stumps)	(metres wide of centre stump)
Measurement Uncertainty	±0.0121	±0.0152	±0.0074	±0.672	±0.800	±0.90	±1.12	±0.40	±0.0116	±0.0077
Mean	-0.788	1.163	2.107	60.69	17.96	-3.7	43.0	-3.2	15.260	-0.381
Max	-0.242	1.790	2.376	78.39	36.80	85.0	180.0	9.7	20.120	0.748
Min	-1.952	0.362	1.972	39.10	1.82	-55.0	-179.0	-19.2	12.936	-0.968
S.D.	0.2994	0.2806	0.0940	14.970	8.200	32.31	136.24	6.58	1.6247	0.2821
Standard Error	0.0353	0.0331	0.0111	1.763	0.966	3.81	16.05	0.78	0.1914	0.0332

Table 3.6.9: The delivery variables of all deliveries recorded.

The maximum and minimum values for each of the variables form the operating range that a cricket bowling machine must perform in order to recreate the deliveries witnessed during testing. A machine must be able to output deliveries with speeds ranging between 78.39 mph and 39.10 mph and impart spin rates of between 1.82 rps and 36.8 rps. Additionally, the head of the machine must be able to launch balls from 9.7 degrees above the horizontal plane to 19.2 degrees below the horizontal plane (see figure 3.6.9).

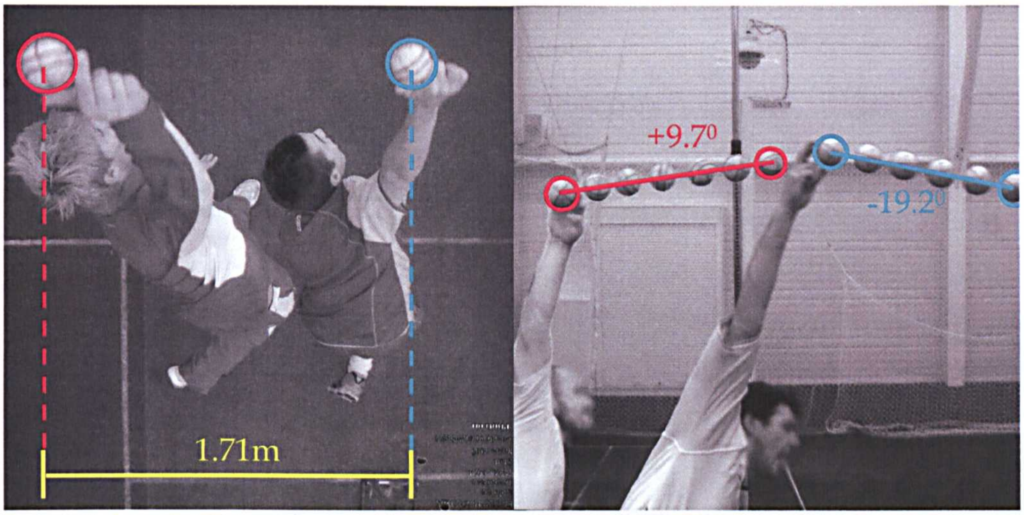


Figure 3.6.9: Still images taken from video data illustrating the differences seen in release position in the X plane (left) and the vertical launch angle (right).

A bowling machine must be able to move to 1.952 metres wide of centre stump and to within 0.242 metres of centre stump, thus needing to translate 1.71 metres in the X plane (see figure 3.6.9). In the Y plane the machine must release balls from 0.362 metres to 1.79 metres in front of the stumps and between 1.972 metres and 2.376 metres above the ground (Z plane) if it is able to recreate the deliveries seen during testing.

The range of release speeds and spin rates seen for the spin and pace bowlers are compared in figure 3.6.10. Mean values are plotted with error bars representing the total spread of data seen throughout testing:

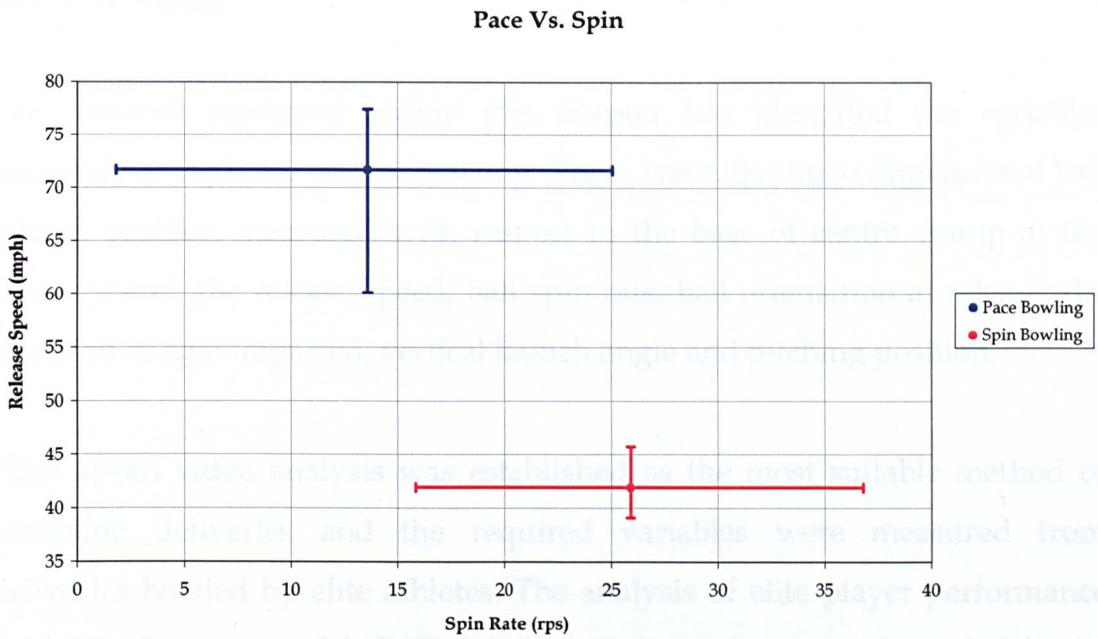


Figure 3.6.10: A graphical representation of the release speed and spin rate spread for the pace and spin bowlers tested. Mean values are plotted with error bars representing the maximum and minimum values seen.

The data displayed in figure 3.6.10 indicates that spin bowlers release the ball more slowly than pace bowlers (maximum spin release speed = 46.47 mph Vs. 78.39 mph maximum pace release speed) and they also impart more spin onto the ball (maximum spin rate for spin bowler = 36.80 rps Vs. 25.04 rps maximum spin rate for pace bowler), this is not contrary to prior knowledge of human bowling performance. However from these data it can be seen that there is a considerably greater range in the release speeds seen in pace bowling than in spin bowling (pace range = 60.13 - 78.79 mph (18.26 mph) Vs. spin range = 39.10 – 46.47 mph (7.37 mph)). The range in spin rate imparted for both spin and pace bowlers is surprisingly similar with the range for pace bowlers 23.22 rps (1.82 - 25.04 rps) and for spin bowlers 20.96 rps (15.84 - 36.80 rps).

3.7: Conclusions

The research presented within this chapter has identified the variables necessary to replicate cricket bowling. These were: the three dimensional ball release position measured with respect to the base of centre stump at the bowler's end, the release speed, ball spin rate, ball orientation at release, the direction of spin imparted, vertical launch angle and pitching position.

High speed video analysis was established as the most suitable method of analysing deliveries and the required variables were measured from deliveries bowled by elite athletes. The analysis of elite player performance established a range of ball flight characteristics for a number of delivery variations (e.g. leg break, slider flipper, googly) and defined the operating range of output variables for a bowling machine tasked with replicating elite human performance.

4: Elite Match - Play Analysis:

The aim of the research presented in this Chapter is to: (i) supplement the bowling delivery parameters knowledge gained during the high speed video analysis of player performance seen in Chapter 3 with data from two of the world's top bowlers performing under match conditions and (ii) illustrate typical delivery strategies (i.e. sequences of deliveries) adopted when facing different batsmen at different stages within matches. This analysis is focused upon elite bowling performance during the 2006/07 Ashes test series between Australia and England with the aim of addressing the following research questions:

- What are the ball flight characteristics of deliveries released by elite bowlers under match conditions?
- What are the delivery variations released by bowlers in a match scenario?
- How are these delivery variations classified from ball flight data?
- How do ball flight characteristics vary when bowling to right and left handed batsmen?
- What are the delivery strategies adopted by elite bowlers in a match scenario?

4.1: Data Structure:

The data features two bowlers from the same team: one fast bowler and one spin bowler, who, at the time of competition were placed fourth and ninth in the top test match bowlers in the ICC world rankings. The data analysed in this Chapter have been derived from the HawkEye ball tracking system present at each of the venues throughout the Ashes series. Where necessary, these quantitative data have been supplemented with additional information from expert sources to support informed judgements when classifying ball type. The structure of the data and how it has been broken down for analysis are detailed in Figure 4.1.1.

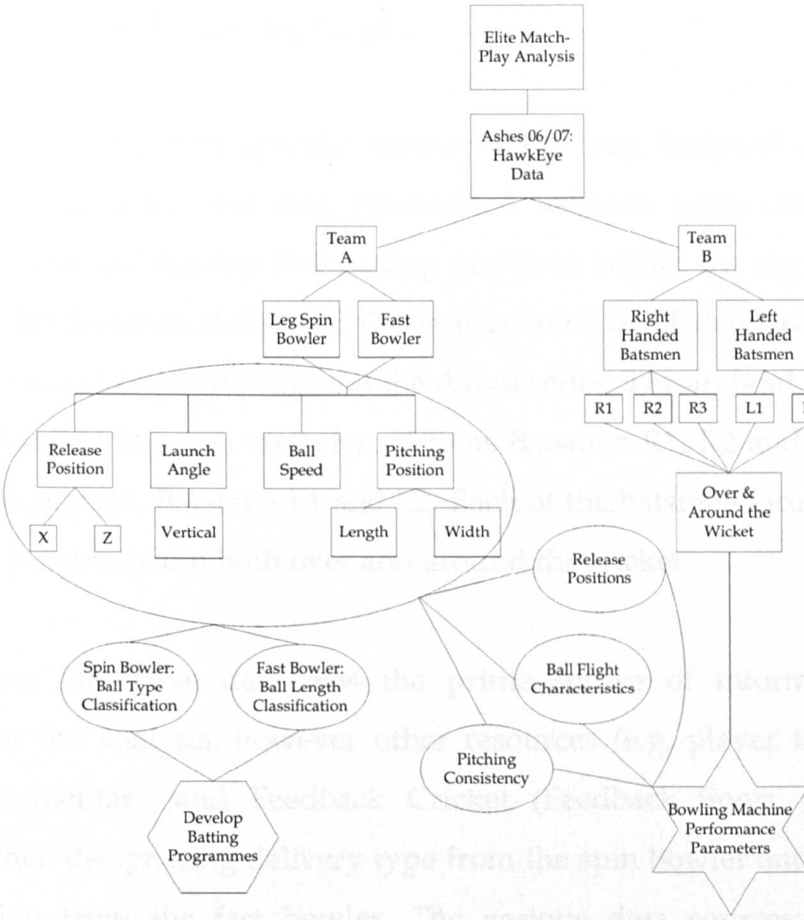


Figure 4.1.1: The breakdown of the HawkEye data analysed during this chapter.

The HawkEye system measured the same variables (e.g. release speed, pitching length, etc) for both of the bowlers. The focus of this chapter is on comparisons of: (i) the ball release position in the X and Z planes, (representing the release position wide of centre stump and the release height from the ground respectively), (ii) the vertical launch angle of the ball, (iii) the release speed of the ball and (iv) its pitching length and width with respect to the centre stump at the bowlers end. Hawkeye does not compute the release position in the Y plane nor does it determine values for spin rate or ball orientation at release.

From these raw data it was possible to classify the ball type of each delivery bowled by the spin bowler and to categorise each delivery bowled by the pace bowler based upon the pitching length.

Deliveries bowled to five specific batsmen have been focussed upon. Three right-handed batsmen and two left-handed batsmen were chosen. These players represented the top five batting positions within the opposing team and were the batsmen that faced the largest number of deliveries from the two bowlers in question throughout the Ashes series. Throughout this chapter the right-handed batsmen are referred to as Batsmen R1, R2 and R3 and the left-handed players, Batsmen L1 and L2. Each of the batsmen faced deliveries from both bowlers, from both over and around the wicket.

Quantitative HawkEye data was the prime source of information used throughout the analysis, however other resources (e.g. player testing data, expert commentary and Feedback Cricket (Feedback Sport, 2008) were utilised when deciphering delivery type from the spin bowler and ball length classification from the fast bowler. The various data sources referred to during this chapter are reviewed in Table 4.1.1. Within the table a tick represents information that can be determined from a particular source with a cross used to indicate that the particular information is unavailable.

	Data Type	Under Match Conditions	Ball Type	Delivery Length Classification	Release Position X	Release Position Y	Release Position Z	Speed	Spin Rate	Ball Orientation at Release	Predominant Spin Direction	Vertical Launch Angle	Horizontal Launch Angle	Pitching Length	Pitching Width
					(metres wide of centre stump)	(metres from bowler's stumps)	(metres from floor)	(mph)	(rps)	(degrees from normal)	(degrees normal to spin axis)	(degrees from horizontal)	(degrees from normal)	(metres from bowler's stumps)	(metres wide of centre stump)
HawkEye Data	Quantitative	✓	✗	✓	✓	✗	✓	✓	✗	✗	✗	✓	✗	✓	✓
Player Testing Data	Quantitative	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Expert Commentary	Qualitative	✓	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
Feedback Cricket Data	Qualitative	✓	✗	✓	✓	✗	✗	✓	✗	✗	✗	✗	✗	✓	✓

Table 4.1.1: A review of the data sources used and information gained during this chapter.

Note: for the current analysis, (c.f. that undertaken in Chapter 3), four additional columns have been added to Table 4.1.1 (i.e. the data type (i.e.

qualitative or quantitative), whether the information is sampled from a match environment, ball type classification and delivery length classification).

As detailed in Chapter 3, player testing using high speed video data provides the most comprehensive coverage of the variables of interest. However this level of detail cannot currently be undertaken within the match environment since it would significantly affect the game due to the large amount of time and resource required for equipment setup, carrying out the experiments and the need to house the camera within a close proximity to the player being analysed. The HawkEye system was, at the time of writing, the only available analysis tool that provided quantitative data of a cricket bowling delivery from a match environment. HawkEye is an optical system that triangulates the position of a ball in 3-D space from images produced by three orthogonal cameras positioned at the periphery of the field of play sampling at 140 frames per second (see Chapter 3, section 3.2.7). However the system is incapable of measuring the orientation of the ball at release and any rotation the ball undergoes as a consequence of spin imparted by the action of the bowler.

4.2: Spin Bowler:

The HawkEye data from the spin bowler's deliveries were analysed and each delivery was then categorised into one of four delivery types (i.e. leg break, slider, flipper and googly) as used in player testing experiments detailed in Chapter 3. In order to categorise each of the deliveries the ball speed, vertical launch angle and pitching position were compared to the values seen from high-speed video player testing. The deviation angle of the ball post contact with the pitch was also analysed to provide an insight into the amount and direction of spin imparted onto the ball. In addition expert ball by ball commentary was consulted to clarify any deliveries that did not automatically fall into one of the four categories.

The deviation angle of the ball post contact with the pitch with respect to its original target line is presented for four delivery types bowled by the spin bowler in Figure 4.2.1. A negative deviation angle represents a ball moving towards a right handed batsman's off side (i.e. deviating to the left from the bowler's viewpoint), with a positive deviation angle representing movement towards the leg side of a right handed batsman (i.e. deviating to the right). Leg breaks (-3.5 to -5 degrees) and googlys (+3 to +4 degrees) provide the largest deviations from the 0 normal in the data set. The small deviations (in both directions are provided by the slider / flipper / googly classifications (from -ve to +ve deviations respectively). Differentiation within these classifications is not as obvious as for the extreme leg breaks and googlys since there is a large degree of overlap evident in the data.

The red lines drawn onto the graph represent the boundaries used when discerning ball type (see figure 4.2.1).

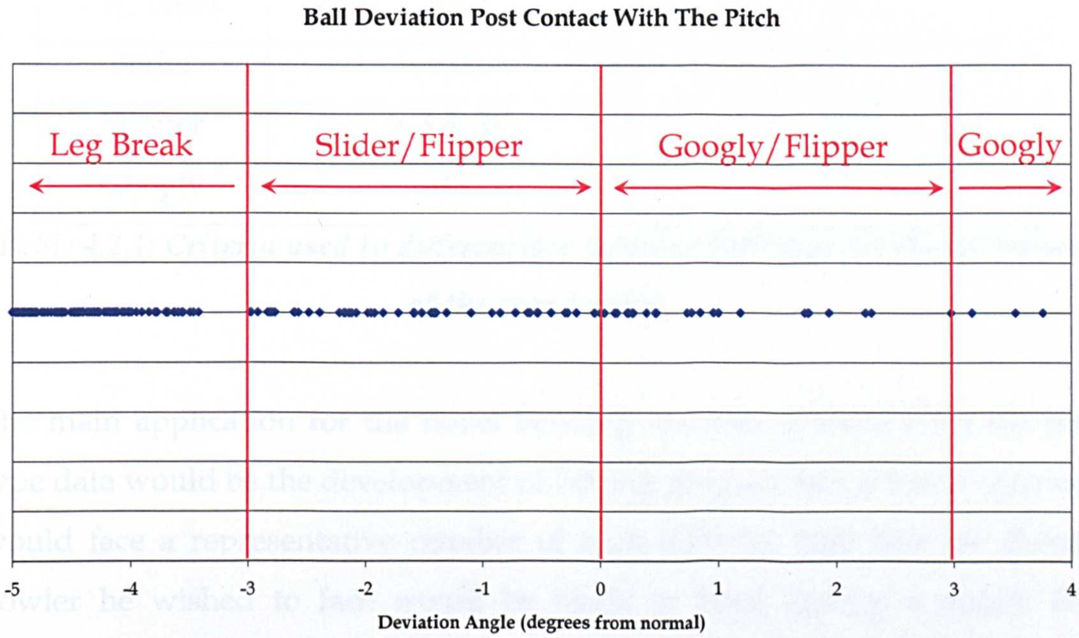


Figure 4.2.1: The level of ball line deviation seen post contact with the pitch and the boundaries used when discerning ball type.

The clearest difference in ball flight characteristics between the four delivery types witnessed during player testing (see figure 3.6.4, Chapter 3) was the vertical launch angle of the flipper delivery. The flipper was released at a flatter angle than any of the other deliveries, 1.8 degrees above the horizontal plane as opposed to 4.2 degrees of the next flattest delivery type, the googly. A midpoint was taken between these two values and a vertical launch angle of 3 degrees above the horizontal plane was the boundary decided upon to differentiate between slider and flipper deliveries and googly and flipper deliveries. The criteria used to differentiate between ball types for the spin bowler are summarised in Table 4.2.1.

	Deviation Angle	**Vertical Launch Angle**
Ball Type	(degrees from normal)	(degrees from horizontal)
Leg Break	≤-3	≥3
Slider	>-3	≥3
Flipper	≥-3 & 3<	<3
Googly	0>	≥3

Table 4.2.1: Criteria used to differentiate between ball type for the deliveries of the spin bowler.

The main application for the novel bowling machine derived from the ball type data would be the development of batting programmes where a batsman would face a representative number of each delivery type that the chosen bowler he wished to face would be likely to bowl during a match. For example, a series of four pie charts displaying the percentage likelihood of each delivery type bowled to the right and left handed batsmen from over and around the wicket are displayed in figures 4.2.2 (a)-(d). If a right handed batsman wanted to face 100 deliveries from over the wicket representative of the ability of the spin bowler analysed, typically 80 deliveries would be leg breaks, 13 would be sliders, 2 flippers and 5 googlys.

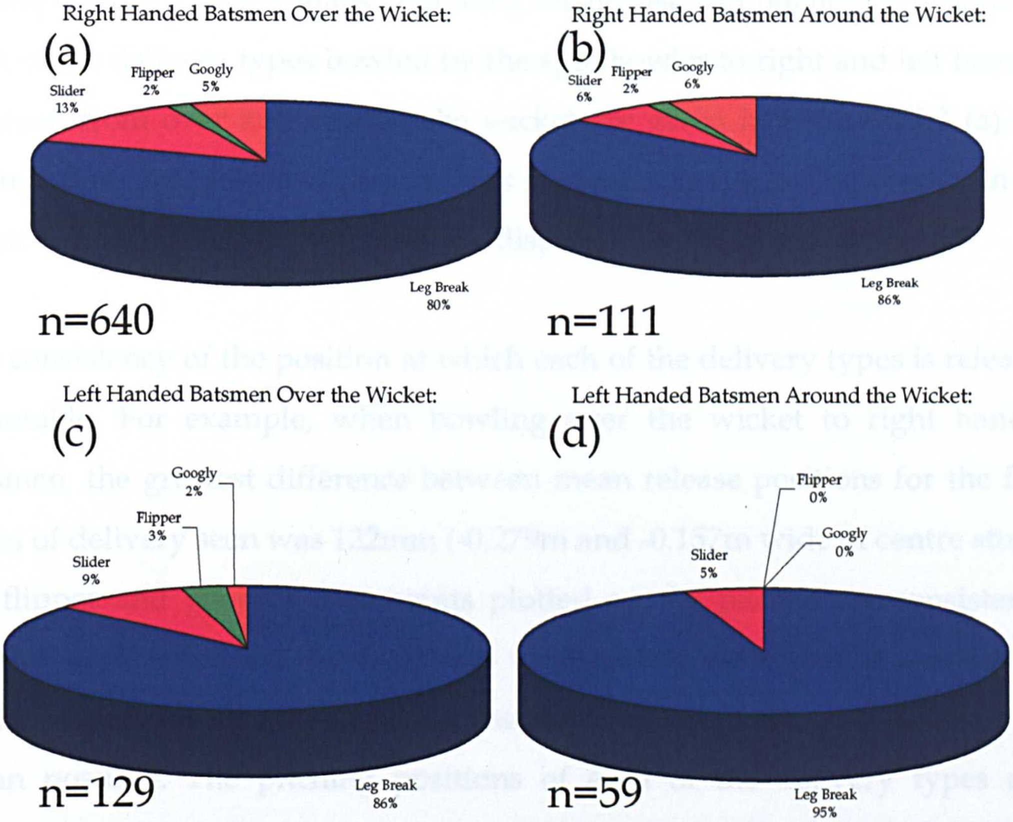


Figure 4.2.2: The likelihood of facing each ball type from the spin bowler for right and left handed batsmen from over and around the wicket.

The leg break is the most likely delivery type a batsman either right handed (average =83%), or left handed (average=90%) will face. In addition when bowling to left handed batsmen from around the wicket the spin bowler uses the least variation in delivery type with just the leg break and slider deliveries witnessed.

A sample of four "pitch-maps" detailing the release and pitching positions for each of the delivery types bowled by the spin bowler to right and left handed batsmen from over and around the wicket are given in Figure 4.2.3 (a)-(d). Mean values are plotted with error bars representing the standard error in the mean. Complete sets of the results are displayed in Appendix B.

The consistency of the position at which each of the delivery types is released is notable. For example, when bowling over the wicket to right handed batsmen, the greatest difference between mean release positions for the four types of delivery seen was 122mm (-0.279m and -0.157m wide of centre stump for flipper and googly). The points plotted on the pitch-maps consistently overlap each other and the error bars representing the standard error in the mean values are often smaller than the actual plotted point representing the mean position. The pitching positions of each of the delivery types also represent a relatively tight grouping; for example, mean pitching lengths of 15.72m, 16.53m, 15.67m and 16.67m from the bowlers stumps for leg break, slider, flipper and googly deliveries respectively when bowling to right handed batsmen from over the wicket. This represents a spread of 1 metre for the mean lengths of the four delivery types with 640 deliveries being analysed. The flipper delivery would appear to be the least controlled delivery type in terms of pitching length with standard error values of ±0.773m, ±0.636m and ±0.563m when bowling to right handed batsmen over the wicket, right handed batsmen around the wicket and left handed batsmen over the wicket respectively. The flipper was however the least bowled of the four delivery types with only 18 deliveries being bowled to the five batsmen during the series.

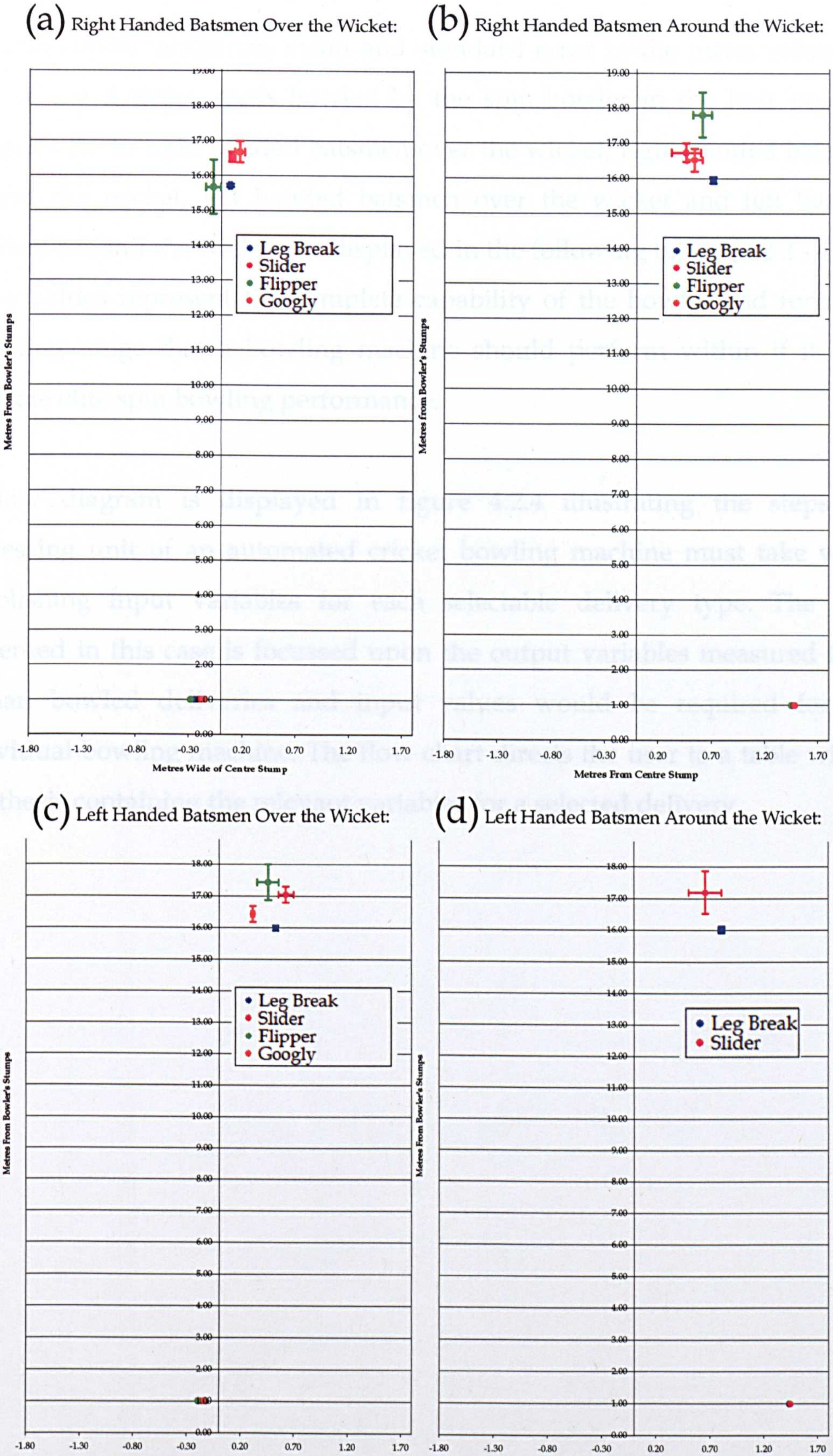


Figure 4.2.3: The pitching positions of the spin bowler to right and left handed batsmen from over and around the wicket.

The maximum, minimum, mean and standard error in the mean values for each of the delivery types bowled by the spin bowler in the four possible scenarios i.e. to right handed batsmen over the wicket, right handed batsmen around the wicket, left handed batsmen over the wicket and left handed batsmen around the wicket are displayed in the following tables (4.2.2 - 4.2.5). These values represent the complete capability of the bowler and form the operating range that a bowling machine should perform within if it is to replicate elite spin bowling performance.

A flow diagram is displayed in figure 4.2.4 illustrating the steps the processing unit of an automated cricket bowling machine must take when establishing input variables for each selectable delivery type. The data presented in this case is focussed upon the output variables measured from human bowled deliveries and input values would be required for the individual bowling machine. The flow chart directs the user to a table within this thesis containing the relevant variables for a selected delivery.

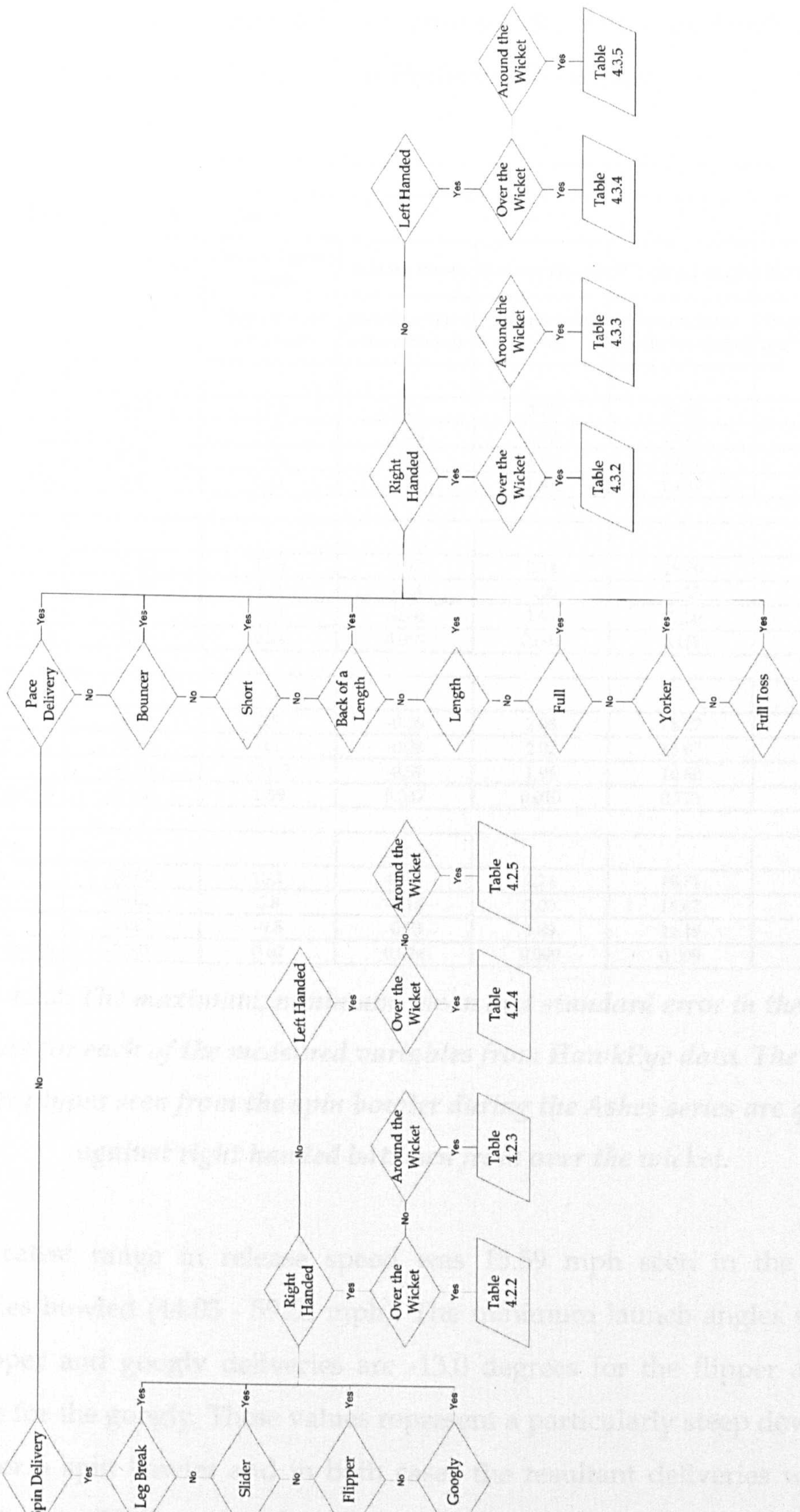


Figure 4.2.4: A flow chart illustrating the steps required to identify the output variables for each selected delivery type.

The data presented in table 4.2.2 summarises the deliveries bowled by the spin bowler to right handed batsmen from over the wicket.

Spin Bowler						
Right Handed Batsmen - Over the Wicket						
	Release Speed	Vertical Launch Angle	Release Width	Release Height	Pitching Length	Pitching Width
	(mph)	(degrees from horizontal)	(metres wide of centre stump)	(metres from floor)	(metres from bowler's stumps)	(metres wide of pitch centre line)
Leg Break						
Max	51.81	12.8	0.12	2.22	18.42	0.82
Mean	47.93	6.7	-0.24	2.02	15.72	0.08
Min	41.80	-3.4	-0.64	1.92	12.52	-0.55
Std. Error (n=514)	0.083	0.11	0.008	0.002	0.039	0.010
Slider						
Max	57.24	13.9	0.07	2.14	19.70	0.69
Mean	48.87	6.9	-0.19	2.00	16.53	0.10
Min	44.47	-1.3	-0.60	1.91	12.00	-0.57
Std. Error (n=82)	0.213	0.26	0.019	0.004	0.151	0.026
Flipper						
Max	52.94	2.9	-0.06	2.08	18.27	0.25
Mean	45.73	0.1	-0.28	2.02	15.67	-0.08
Min	41.85	-13.0	-0.59	1.96	10.68	-0.49
Std. Error (n=12)	0.947	1.39	0.047	0.010	0.773	0.070
Googly						
Max	59.62	13.1	0.04	2.14	18.71	0.81
Mean	49.00	5.8	-0.16	2.00	16.67	0.17
Min	44.03	-9.5	-0.53	1.89	11.49	-0.51
Std. Error (n=32)	0.547	0.62	0.024	0.009	0.309	0.046

Table 4.2.2: The maximum, minimum, mean and standard error in the mean values for each of the measured variables from HawkEye data. The four delivery types seen from the spin bowler during the Ashes series are quoted against right handed batsmen from over the wicket.

The greatest range in release speed was 15.59 mph seen in the googly deliveries bowled (44.03 - 59.62 mph). The minimum launch angles seen for the flipper and googly deliveries are -13.0 degrees for the flipper and -9.5 degrees for the googly. These values represent a particularly steep downward angle for a spin bowler and in both cases the resultant deliveries were the shortest seen (10.68 metres for flipper, 11.49 metres for googly). From this evidence it is possible to say that these deliveries may have been accidental as they are released at a significantly lower angle and pitch significantly shorter than other deliveries seen. Leg spin bowlers, due to the complexity of the bowling action will occasionally release deliveries with unpredictable characteristics resulting in a short length, full toss or pitching particularly wide. There appear to be two distinct delivery lengths bowled by the spin bowler to right handed batsmen from over the wicket. A pitching length of ≈ 15.70 metres is seen for the leg break (15.72 metres) and the flipper (15.67 metres) deliveries while for the slider (16.53 metres) and googly (16.67 metres) a longer pitching length is evident.

The data presented in table 4.2.3 summarises the deliveries bowled by the spin bowler to right handed batsmen from around the wicket.

Spin Bowler						
Right Handed Batsmen - Around the Wicket						
	Release Speed	Vertical Launch Angle	Release Width	Release Height	Pitching Length	Pitching Width
	(mph)	(degrees from horizontal)	(metres wide of centre stump)	(metres from floor)	(metres from bowler's stumps)	(metres wide of pitch centre line)
Leg Break						
Max	51.41	10.6	1.61	2.08	18.47	1.45
Mean	46.56	5.3	1.47	2.01	15.96	0.71
Min	43.56	-1.6	1.35	1.95	13.92	0.10
Std. Error (n=95)	0.182	0.25	0.005	0.003	0.087	0.022
Slider						
Max	51.03	8.8	1.49	2.00	17.27	0.84
Mean	48.60	5.8	1.46	1.98	16.74	0.46
Min	44.84	4.0	1.43	1.97	15.46	-0.12
Std. Error (n=7)	0.921	0.70	0.009	0.004	0.268	0.137
Flipper						
Max	48.87	3.0	1.47	1.99	18.27	0.67
Mean	47.69	2.9	1.45	1.99	17.82	0.61
Min	46.51	2.8	1.44	1.98	17.37	0.55
Std. Error (n=2)	1.667	0.06	0.015	0.009	0.636	0.085
Googly						
Max	52.01	9.6	1.57	2.05	17.19	0.70
Mean	46.35	6.8	1.48	2.01	16.53	0.54
Min	43.32	2.2	1.39	1.97	14.99	0.19
Std. Error (n=7)	1.124	0.99	0.024	0.014	0.329	0.074

Table 4.2.3: The maximum, minimum, mean and standard error in the mean values for each of the measured variables from HawkEye data. The four delivery types seen from the spin bowler during the Ashes series are quoted against right handed batsmen from around the wicket.

From around the wicket, deliveries were released with less "flat" launch angles (i.e. less negative magnitude). Only the minimum launch angle for leg break deliveries was negative (-1.6 degrees) with the lowest launch angle for any of the other delivery types of 2.2 degrees above the horizontal seen in the googly deliveries. Of particular note is the maximum pitching width witnessed for leg break deliveries. Pitching at a distance of 1.45 metres wide of centre stump is wider than the confines of the pitch (1.32 metres wide of centre stump). The shortest pitching lengths of the deliveries bowled from around the wicket to right handed batsmen are fuller than those bowled from over the wicket. The shortest delivery seen from around the wicket pitched at 13.92 metres from the bowlers stumps compared to 10.68 metres seen for the flipper deliveries from over the wicket.

The data presented in table 4.2.4 summarises the deliveries bowled by the spin bowler to left handed batsmen from over the wicket.

Spin Bowler						
Left Handed Batsmen - Over the Wicket						
	Release Speed	Vertical Launch Angle	Release Width	Release Height	Pitching Length	Pitching Width
	(mph)	(degrees from horizontal)	(metres wide of centre stump)	(metres from floor)	(metres from bowler's stumps)	(metres wide of pitch centre line)
Leg Break						
Max	50.33	12.4	0.09	2.10	17.76	1.25
Mean	48.51	6.3	-0.12	2.11	15.98	0.53
Min	44.68	-3.3	-0.49	1.91	13.87	-0.07
Std. Error (n=111)	0.103	0.2	0.009	0.003	0.080	0.020
Slider						
Max	51.31	8.7	0.01	2.08	18.25	1.00
Mean	48.79	5.5	-0.17	2.00	17.04	0.63
Min	44.92	1.5	-0.60	1.85	15.71	0.21
Std. Error (n=12)	0.503	0.58	0.047	0.018	0.255	0.071
Flipper						
Max	49.59	2.6	-0.15	2.11	18.43	0.62
Mean	46.34	1.2	-0.19	2.03	17.43	0.46
Min	44.43	-0.4	-0.24	1.94	16.36	0.26
Std. Error (n=4)	1.299	0.78	0.026	0.042	0.563	0.101
Googly						
Max	47.77	9.2	-0.12	2.02	16.59	0.33
Mean	47.17	6.1	-0.14	2.01	16.42	0.32
Min	46.57	2.9	0.16	1.99	16.24	0.31
Std. Error (n=2)	0.851	4.42	0.029	0.018	0.247	0.014

Table 4.2.4: The maximum, minimum, mean and standard error in the mean values for each of the measured variables from HawkEye data. The four delivery types seen from the spin bowler during the Ashes series are quoted against left handed batsmen from over the wicket.

Of the 129 deliveries released by the spin bowler from over the wicket to left handed batsmen 111 of them were leg breaks (86%). The range in speeds seen for the over the wicket deliveries is considerably smaller than when bowling to right handed batsmen. A maximum range in release speeds of 6.39 mph was seen for the slider deliveries (44.92-51.31 mph) compared to the 15.59 mph seen in the googly deliveries bowled to right handed batsmen from over the wicket (44.03-59.62 mph).

The data presented in table 4.2.5 summarises the deliveries bowled by the spin bowler to left handed batsmen from around the wicket.

Spin Bowler						
Left Handed Batsmen - Around the Wicket						
	Release Speed	Vertical Launch Angle	Release Width	Release Height	Pitching Length	Pitching Width
	(mph)	(degrees from horizontal)	(metres wide of centre stump)	(metres from floor)	(metres from bowler's stumps)	(metres wide of pitch centre line)
Leg Break						
Max	50.90	10.4	1.55	2.19	17.65	1.25
Mean	48.18	6.0	1.44	2.03	16.02	0.81
Min	43.82	-3.8	1.30	1.95	13.91	0.29
Std. Error (n=56)	0.178	0.29	0.008	0.006	0.110	0.028
Slider						
Max	48.57	6.8	1.50	2.01	17.99	0.86
Mean	48.01	5.0	1.45	2.01	17.20	0.66
Min	47.55	3.4	1.38	2.00	16.15	0.43
Std. Error (n=3)	0.368	1.24	0.047	0.006	0.673	0.153

Table 4.2.5: The maximum, minimum, mean and standard error in the mean values for each of the measured variables from HawkEye data. The two delivery types seen from the spin bowler during the Ashes series are quoted against left handed batsmen from around the wicket.

The first thing to note from the data presented in table 4.2.5 is that only two delivery types (leg break and slider) were attempted by the spin bowler to left handed batsmen from around the wicket. Of the 59 deliveries bowled, only 3 of them were classified as sliders (see table 4.2.5) representing a 5.1% chance of facing a slider delivery. Hence a left handed batsmen facing the spin bowler from around the wicket has a 94.9% chance of facing a leg break delivery.

All of the deliveries bowled from around the wicket were released within a 0.25 metre position in the X plane (release width range: 1.30 - 1.55 metres wide of centre stump). The pitching lengths of deliveries released from over and around the wicket to left handed batsmen do not appear to change significantly. The mean leg break length from over the wicket was 15.98 metres compared to 16.02 metres from around the wicket. Similarly, for the slider deliveries bowled from over the wicket a mean pitching length of 17.04 metres was recorded while from around the wicket 17.20 metres was seen.

4.3: Pace Bowler:

For the pace bowler, delivery type was classified according to its pitching length to be consistent with the analysis undertaken during player testing in Chapter 3 (see section 3.6, table 3.6.8). The categories were taken from the options available to analysts using Feedback Cricket software which is a computer program used by teams' expert performance analysts to evaluate manually each delivery from live video data. The delivery length classifications are: bouncer, short, back of a length, length, full, yorker and full toss. These delivery lengths are illustrated in figure 4.3.1.

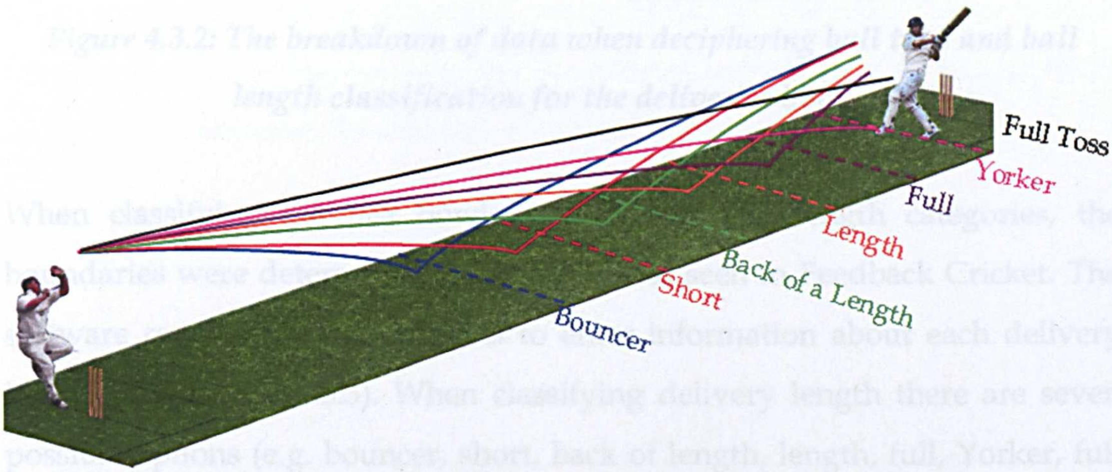


Figure 4.3.1: The delivery length classifications seen in Feedback Cricket.

The boundaries for each of the length classifications were derived from values identified by Justham (2007). The classification process adopted for fast and spin bowling deliveries is illustrated in Figure 4.3.2:

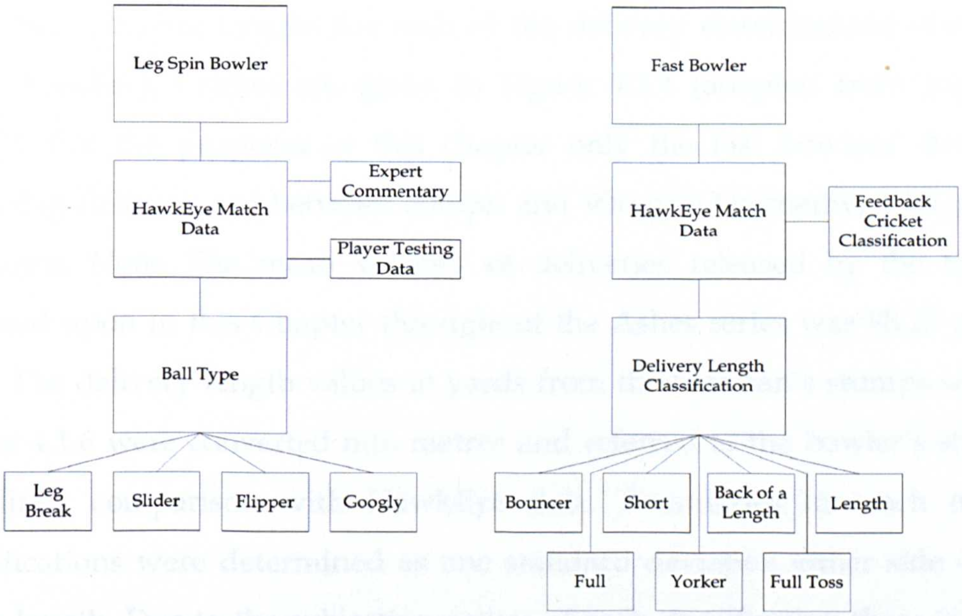


Figure 4.3.2: The breakdown of data when deciphering ball type and ball length classification for the deliveries bowled.

When classifying the fast bowler's deliveries into length categories, the boundaries were determined using the values seen in Feedback Cricket. The software requires trained analysts to enter information about each delivery bowled (see figure 4.3.3). When classifying delivery length there are seven possible options (e.g. bouncer, short, back of length, length, full, Yorker, full toss see table 4.1.3). Additionally the line of the delivery, shot played and the number of runs scored are recorded.

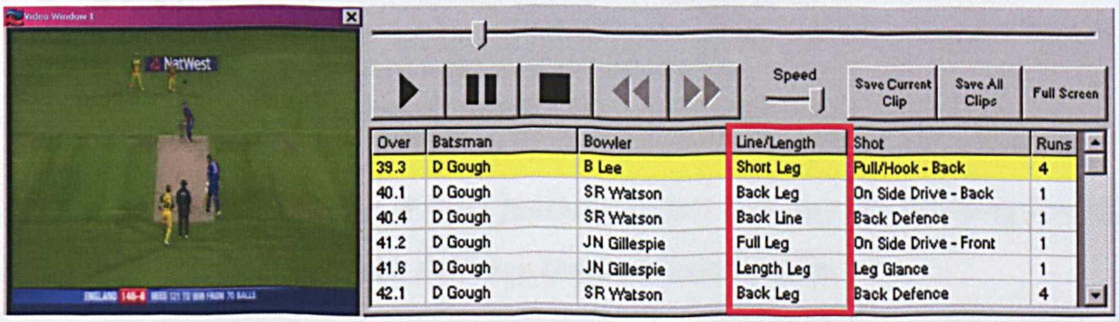


Figure 4.3.3: A screenshot taken from Feedback Cricket software. The column describing each delivery's line and length is highlighted.

The mean pitching lengths for each of the delivery classifications observed using Feedback Cricket are given in Figure 4.3.4 (adapted from Justham (2007)). For the purposes of this chapter only the fast bowlers' data i.e. (releasing deliveries of between 80mph and 90mph (Abernethy, 1981)) is of relevance. Note: The mean velocity of deliveries released by the bowler focussed upon in this Chapter throughout the Ashes series was 88.23 ±2.902 mph. The delivery length values in yards from the batsman's stumps seen in Figure 4.1.6 were converted into metres and referred to the bowler's stumps for direct comparison with HawkEye data. Boundaries for each of the classifications were determined as one standard deviation either side of the mean length. Due to the subjective nature of each classification there is some inevitable overlapping between the boundaries hence a mid point was taken as the divide between the overlapping points.

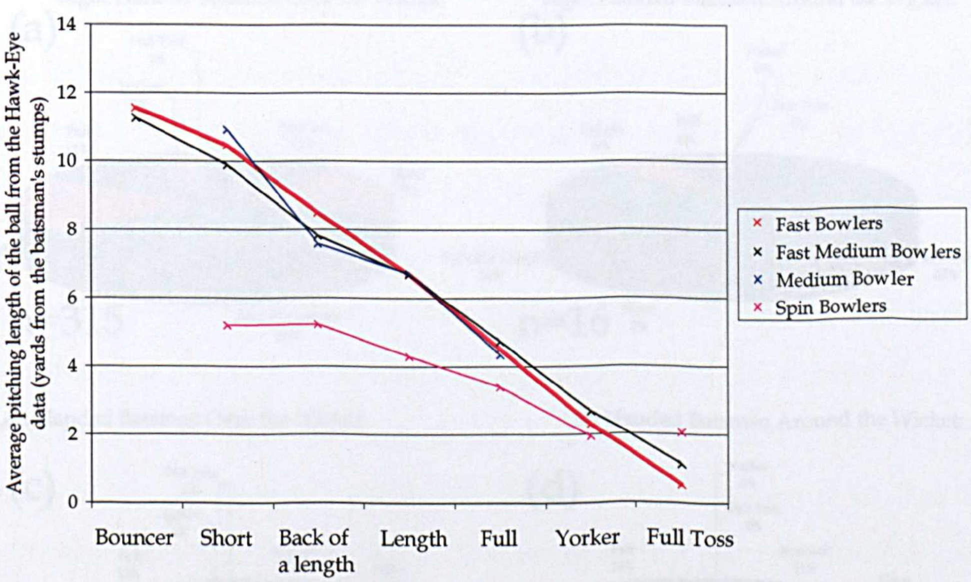


Figure 4.3.4: Graph adapted from Justham (2007) defining the pitching length for each delivery length classification.

The boundaries defined for each of the delivery length classifications are summarised in table 4.3.1.

Delivery Length Classification	Pitching Length (metres from bowler's stumps) (+/-0.005m)
Bouncer	Up to 9.94
Short	9.95-11.51
Back of a Length	11.52-13.12
Length	13.13-14.78
Full	14.79-17.30
Yorker	17.31-19.17
Full Toss	Above 19.18

Table 4.3.1: The boundaries defined for each of the delivery length classes seen throughout the analysis of the elite fast bowler.

The likelihood of facing each delivery length for right and left handed batsmen from both over and around the wicket from the fast bowler under investigation is displayed in a series of four pie charts (see figures 4.3.5 (a)-(d)):

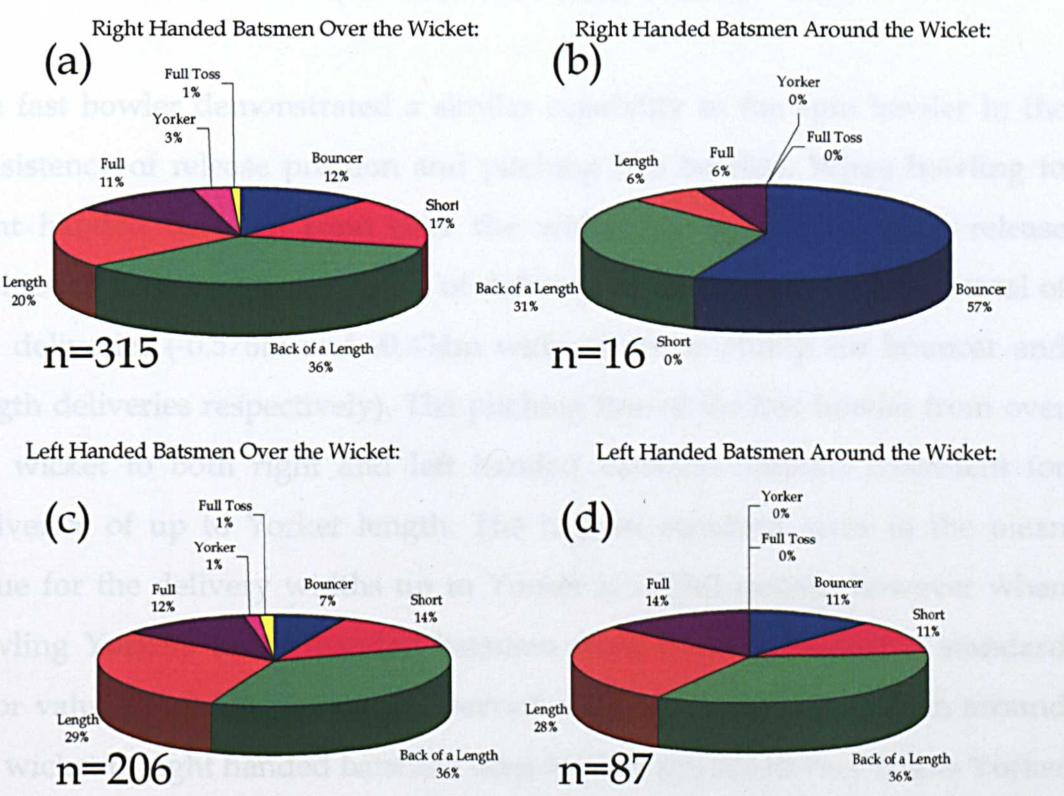


Figure 4.3.5: The likelihood of facing each delivery length from the fast bowler for right and left handed batsmen from over and around the wicket.

When the fast bowler delivers from around the wicket to right handed batsmen the likelihood of facing a bouncer is significant (i.e. 57%). Shorter deliveries form the majority of the balls from this bowler (i.e. Σ (Back of a Length + Short + Bouncer) = 65%, 88%, 57% and 58% for cases (a), (b), (c) and (d) respectively). It is interesting to note that there are significant differences with the deliveries from over the wicket and around the wicket when bowling to right handed batsmen. For example his around the wicket deliveries are particularly intimidating i.e. 88% shorter deliveries, only 6% at a length and 6% full when compared with 65% shorter, 20% length, 11% full and 4% Yorker and full toss from over the wicket. In contrast there appears to be much less variation in his deliveries to left handed batsmen when bowling either over or around the wicket. In both cases, shorter deliveries account for approximately 60% of the balls (~36% classified as Back of a Length), length ~30% and fuller deliveries (i.e. full, full toss and Yorker) ~ 14%.

The fast bowler demonstrated a similar capability to the spin bowler in the consistency of release position and pitching line bowled. When bowling to right handed batsmen from over the wicket the spread of mean release positions for the seven categories of delivery length was 142mm for a total of 315 deliveries (-0.576m and -0.434m wide of centre stump for bouncer and length deliveries respectively). The pitching line of the fast bowler from over the wicket to both right and left handed batsmen remains consistent for deliveries of up to Yorker length. The highest standard error in the mean value for the delivery widths up to Yorker is ±0.042 metres, however when bowling Yorkers to left handed batsmen from over the wicket, a standard error value of ±0.329 metres is observed. Only when he bowls from around the wicket to right handed batsmen does his line appear to vary below Yorker length (see figure 4.3.6 (b)), the data for this scenario is however influenced by the limited number or deliveries bowled by the fast bowler to right handed batsmen from around the wicket (i.e. 16).

The consistency in pitching position is clear in figures 4.3.6 (a), (c) and (d) with small error bars representing minimal variation in both length (average ±0.15 m) and line (average ±0.03 m), emphasising the control the bowler has even when bowling at considerable pace.

Against the left handed batsmen two tactics appear to have been used. When bowling over the wicket the ball is angled across the batsman (i.e. released from over the wicket, passing left handed batsmen's stumps on the off side), looking for an outside edge to the wicket keeper or slip fielders. When bowling around the wicket, the line is more focussed upon the batsman's body (i.e. released from around the wicket, passing left handed batsmen's stumps on the leg side), bowling a tighter line closer to the stumps where there is an increased chance of bowling the batsman out or making him play with the bat closer to his body, reducing the length of the lever to strike the ball with and hence the quality of the bat to ball impact.

The release and pitching positions for each of the delivery length classes bowled by the fast bowler to right and left handed batsmen from over and around the wicket are displayed in a series of four pitch maps in figures 4.3.6 (a)-(d). Mean values are plotted with error bars representing the standard error in the mean. Complete details are given in Appendix B.

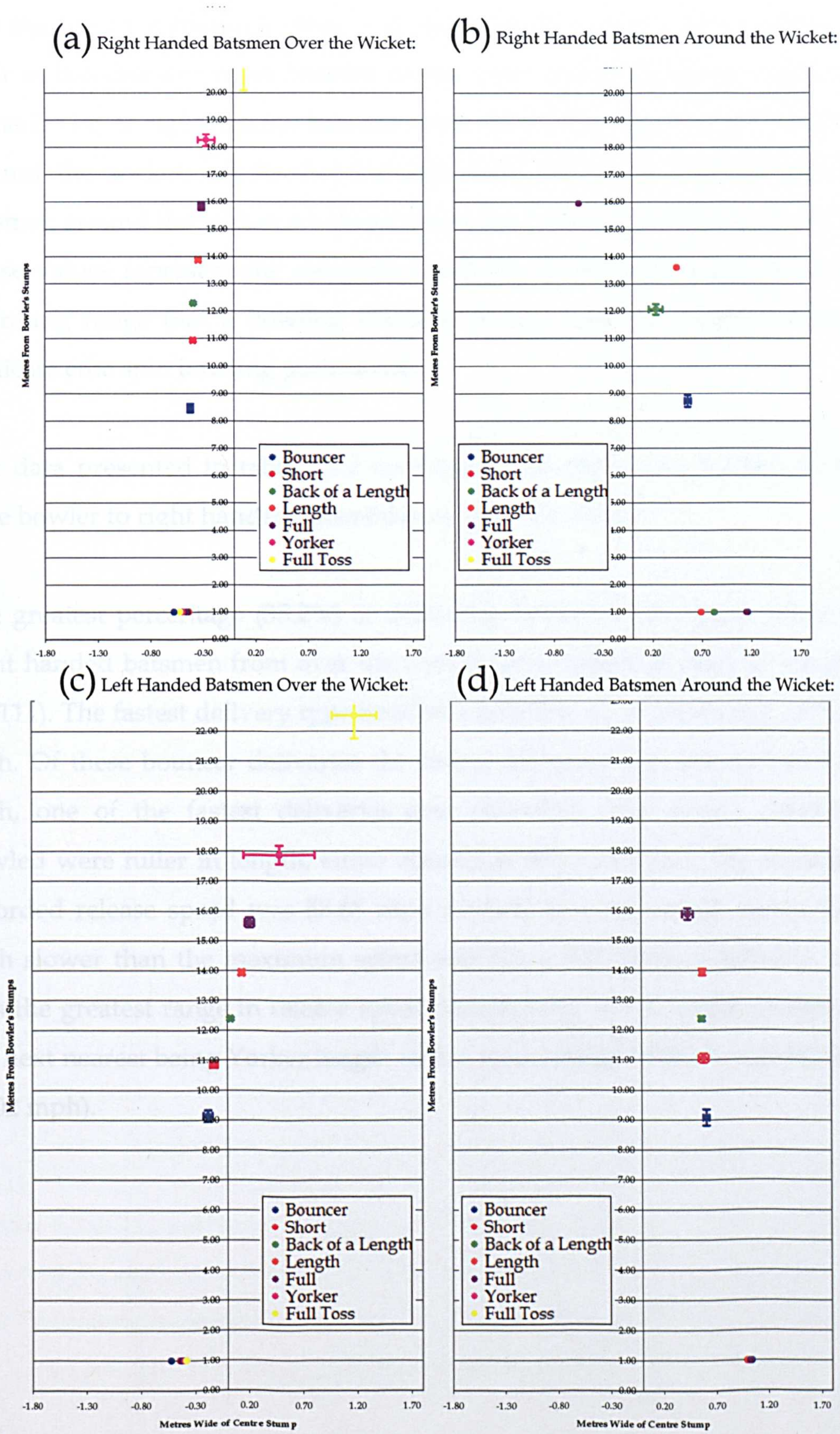


Figure 4.3.6: The pitching positions of the fast bowler to right and left handed batsmen from over and around the wicket.

The maximum, minimum, mean and standard error in the mean values for each of the delivery types bowled by the pace bowler in the four possible scenarios i.e. to right handed batsmen over the wicket, right handed batsmen around the wicket, left handed batsmen over the wicket and left handed batsmen around the wicket are displayed in the following tables (4.3.2 - 4.3.5). These values represent the complete capability of the bowler and form the operating range that a bowling machine should perform within if it is to replicate elite spin bowling performance.

The data presented in table 4.3.2 summarises the deliveries bowled by the pace bowler to right handed batsmen from over the wicket.

The greatest percentage (35.2%) of deliveries bowled by the pace bowler to right handed batsmen from over the wicket were classed as back of a length (n=111). The fastest delivery type bowled was bouncers at an average of 92.88 mph. Of these bouncer deliveries the fastest recorded was released at 99.92 mph, one of the fastest deliveries ever recorded. Any slower deliveries bowled were fuller in length, either classed as full or Yorker. The minimum recorded release speed was 58.68 mph pitched at a full length, some 32.04 mph slower than the maximum speed seen for a full pitched delivery. This was the greatest range in release speed seen for any of the length categories, the next nearest being Yorker length with a speed range of 29.77 mph (62.25 - 92.02 mph).

Fast Bowler						
Right Handed Batsmen - Over the Wicket						
	Release Speed	Vertical Launch Angle	Release Width	Release Height	Pitching Length	Pitching Width
	(mph)	(degrees from horizontal)	(metres wide of centre stump)	(metres from floor)	(metres from bowler's stumps)	(metres wide of pitch centre line)
Bouncer						
Max	99.92	1.5	-0.29	2.09	9.82	-0.10
Mean	92.88	-2.3	-0.58	2.01	8.45	-0.42
Min	83.85	-7.3	-0.88	1.93	6.68	-0.65
Std. Error (n=37)	0.364	0.30	0.030	0.008	0.148	0.026
Short						
Max	92.18	2.5	-0.26	2.07	11.47	-0.12
Mean	87.86	-1.3	-0.47	1.99	10.92	-0.39
Min	80.10	-3.6	-0.81	1.94	9.94	-0.74
Std. Error (n=54)	0.320	0.19	0.021	0.004	0.055	0.019
Back of a Length						
Max	92.19	1.9	-0.23	2.24	13.11	0.06
Mean	88.14	-1.1	-0.45	1.99	12.28	-0.39
Min	80.73	-5.5	-0.84	1.93	11.51	-0.72
Std. Error (n=111)	0.188	0.13	0.013	0.004	0.046	0.014
Length						
Max	90.68	3.8	-0.24	2.09	14.77	0.02
Mean	87.76	-1.2	-0.43	1.98	13.86	-0.34
Min	82.42	-6.9	-0.88	1.92	13.13	-0.71
Std. Error (n=64)	0.218	0.22	0.017	0.004	0.058	0.021
Full						
Max	90.72	7.6	-0.26	2.01	17.16	-0.01
Mean	87.18	-0.8	-0.45	1.97	15.82	-0.31
Min	58.68	-5.3	-0.76	1.92	14.81	-0.67
Std. Error (n=36)	0.857	0.40	0.139	0.004	0.135	0.028
Yorker						
Max	92.02	9.9	-0.31	2.00	19.11	0.19
Mean	85.94	0.0	-0.50	1.97	18.25	-0.26
Min	62.25	-3.7	-0.74	1.92	17.36	-0.50
Std. Error (n=10)	2.853	1.22	0.053	0.009	0.218	0.081
Full Toss						
Max	92.02	-1.5	-0.32	1.95	22.56	0.30
Mean	89.83	-1.6	-0.52	1.93	21.05	0.10
Min	87.95	-2.0	-0.65	1.91	19.92	-0.09
Std. Error (n=3)	1.458	0.19	0.122	0.013	0.964	0.138

Table 4.3.2: The maximum, minimum, mean and standard error in the mean values for each of the measured variables from HawkEye data. The seven delivery length classifications seen from the fast bowler during the Ashes series are quoted against right handed batsmen from over the wicket.

The data presented in table 4.3.3 summarises the deliveries bowled by the pace bowler to right handed batsmen from around the wicket.

Fast Bowler						
Right Handed Batsmen - Around the Wicket						
	Release Speed	**Vertical Launch Angle**	**Release Width**	**Release Height**	**Pitching Length**	**Pitching Width**
	(mph)	(degrees from horizontal)	(metres wide of centre stump)	(metres from floor)	(metres from bowler's stumps)	(metres wide of pitch centre line)
Bouncer						
Max	90.25	1.3	1.25	2.08	9.34	0.71
Mean	88.82	-1.7	1.16	2.03	8.72	0.56
Min	87.04	-4.0	1.08	2.00	7.39	0.44
Std. Error (n=9)	0.359	0.56	0.021	0.009	0.208	0.034
Back of a Length						
Max	88.78	-0.6	1.20	2.31	12.42	0.41
Mean	85.90	-2.8	0.82	2.23	12.06	0.24
Min	84.54	-4.2	0.69	1.99	11.53	0.09
Std. Error (n=5)	0.857	0.72	0.107	0.068	0.187	0.071
Length						
Mean (n=1)	84.92	-2.6	0.69	2.28	13.59	0.45
Full						
Mean (n=1)	85.80	-2.1	1.15	1.97	15.94	-0.54

Table 4.3.3: The maximum, minimum, mean and standard error in the mean values for each of the measured variables from HawkEye data. The four delivery length classifications seen from the fast bowler during the Ashes series are quoted against right handed batsmen from around the wicket.

The pace bowler released few deliveries from around the wicket to right handed batsmen (n = 16). Of the 16 deliveries bowled, 14 of them were classed as back of a length or shorter indicating an aggressive tactic employed when bowling from around the wicket. There is a comparatively small range in release speeds seen for the around the wicket deliveries, a range of 5.71 mph for all deliveries bowled (84.54 – 90.25 mph).

The data presented in table 4.3.4 summarises the deliveries bowled by the pace bowler to left handed batsmen from over the wicket.

Fast Bowler						
Left Handed Batsmen - Over the Wicket						
	Release Speed	Vertical Launch Angle	Release Width	Release Height	Pitching Length	Pitching Width
	(mph)	(degrees from horizontal)	(metres wide of centre stump)	(metres from floor)	(metres from bowler's stumps)	(metres wide of pitch centre line)
Bouncer						
Max	96.23	0.6	-0.25	2.33	9.93	0.01
Mean	90.02	-2.9	-0.52	2.04	9.14	-0.18
Min	78.23	-5.8	-0.83	1.96	7.89	-0.61
Std. Error (n=14)	1.306	0.36	0.047	0.026	0.182	0.044
Short						
Max	96.30	9.7	-0.28	2.31	11.50	0.31
Mean	88.80	-1.4	-0.43	2.01	10.85	-0.12
Min	82.26	-6.8	-0.76	1.93	10.04	-0.48
Std. Error (n=28)	0.699	0.54	0.027	0.017	0.098	0.034
Back of a Length						
Max	94.23	1.9	-0.21	2.34	13.12	0.37
Mean	88.44	-2.1	-0.38	2.00	12.40	0.03
Min	79.54	-9.3	-0.80	1.93	11.58	-0.31
Std. Error (n=73)	0.312	0.24	0.012	0.008	0.051	0.017
Length						
Max	93.23	1.2	-0.24	2.32	14.75	0.66
Mean	87.48	-1.3	-0.39	2.01	13.93	0.14
Min	77.92	-4.5	-0.78	1.94	13.15	-0.30
Std. Error (n=60)	0.345	0.14	0.015	0.009	0.074	0.023
Full						
Max	89.81	7.1	-0.28	2.31	17.27	0.57
Mean	87.00	-1.7	-0.43	2.04	15.61	0.21
Min	83.80	-4.9	-0.79	1.94	14.80	-0.17
Std. Error (n=25)	0.312	0.47	0.034	0.024	0.163	0.042
Yorker						
Max	89.34	-1.5	-0.34	1.97	18.37	0.91
Mean	88.71	-4.4	-0.40	1.96	17.86	0.49
Min	88.32	-7.8	-0.45	1.93	17.55	-0.01
Std. Error (n=3)	0.394	2.24	0.058	0.024	0.317	0.329
Full Toss						
Max	88.14	-3.8	-0.34	2.00	23.15	1.36
Mean	87.63	-4.5	-0.38	1.99	22.52	1.19
Min	86.61	-4.8	-0.40	1.96	21.25	0.85
Std. Error (n=3)	0.628	0.41	0.032	0.022	0.778	0.209

Table 4.3.4: The maximum, minimum, mean and standard error in the mean values for each of the measured variables from HawkEye data. The seven delivery length classifications seen from the fast bowler during the Ashes series are quoted against left handed batsmen from over the wicket.

The slowest delivery seen from the pace bowler to left handed batsmen from over the wicket was 77.92 mph, some 19.24 mph faster than the slowest delivery seen to right handed batsmen (58.68 mph). This would suggest that no "slower balls" were attempted by the pace bowler to the left handed batsmen. As previously seen when bowling to right handed batsmen, the majority (55.8%) of deliveries bowled pitched at back of a length or shorter (115 of 206 deliveries bowled to left handed batsmen from over the wicket). Very few deliveries (n=6 (2.9%)) were bowled at Yorker length or full toss. The bowler exhibited a high level of control in release speed, the range in mean release speed was 3.02 mph (87.00 - 90.02 mph).

The data presented in table 4.3.5 summarises the deliveries bowled by the pace bowler to left handed batsmen from around the wicket.

Fast Bowler						
Left Handed Batsmen - Around the Wicket						
	Release Speed	Vertical Launch Angle	Release Width	Release Height	Pitching Length	Pitching Width
	(mph)	(degrees from horizontal)	(metres wide of centre stump)	(metres from floor)	(metres from bowler's stumps)	(metres wide of pitch centre line)
Bouncer						
Max	98.35	1.6	1.14	2.19	9.92	0.76
Mean	89.87	-1.3	1.03	2.05	9.09	0.61
Min	77.61	-3.2	0.88	1.97	7.62	0.46
Std. Error (n=10)	1.706	0.56	0.026	0.026	0.271	0.030
Short						
Max	92.05	1.0	1.10	2.09	11.48	0.84
Mean	89.35	-1.1	1.00	2.04	11.08	0.59
Min	87.05	-2.4	0.90	1.97	10.30	0.40
Std. Error (n=10)	0.524	0.39	0.018	0.016	0.154	0.045
Back of a Length						
Max	93.61	2.1	1.11	2.14	13.09	0.76
Mean	90.00	-0.4	1.01	2.01	12.40	0.57
Min	86.79	-5.0	0.94	1.87	11.59	0.36
Std. Error (n=31)	0.336	0.27	0.008	0.011	0.083	0.021
Length						
Max	93.15	0.6	1.10	2.09	14.75	0.71
Mean	89.59	-1.3	0.99	2.01	13.96	0.58
Min	85.14	-7.4	0.86	1.94	13.13	0.41
Std. Error (n=24)	0.373	0.36	0.013	0.009	0.106	0.020
Full						
Max	92.11	0.5	1.08	2.06	17.06	0.66
Mean	88.65	-1.6	1.02	2.01	15.90	0.44
Min	86.47	-3.8	0.96	1.97	15.17	0.09
Std. Error (n=12)	0.462	0.44	0.012	0.010	0.186	0.053

Table 4.3.5: The maximum, minimum, mean and standard error in the mean values for each of the measured variables from HawkEye data. The five delivery length classifications seen from the fast bowler during the Ashes series are quoted against left handed batsmen from around the wicket.

The first thing to note from this set of data is the lack of any full toss or Yorker deliveries bowled to left handed batsmen from around the wicket. The majority of deliveries pitched at back of a length or shorter (Σ Bouncer, Short, Back of a Length = 51 deliveries = 58.6%). Additionally there were no slower deliveries attempted by the pace bowler from around the wicket to left handers, the slowest release speed recorded was a bouncer at 77.61 mph which is typical of a "loosener" delivery from a fast bowler. The fastest release speed recorded was 98.35 mph, also a bouncer, the category with the largest range in release speeds (10.74 mph).

4.4: Discussion:

The maximum and minimum values seen for each of the measured variables for all deliveries bowled by the elite spin bowler to all five batsmen during the Ashes series are displayed in table 4.4.1. These values represent the operating range any bowling machine replicating elite human performance must be able to achieve.

Spin Bowler: All Batsmen						
	Release Speed	Launch Angle	Release Width	Release Height	Pitching Length	Pitching Width
	(mph)	(degrees from horizontal)	(metres from centre stump)	(metres from floor)	metres from bowler's stumps)	(metres from pitch centre)
Max	59.62	13.9	1.609	2.523	19.70	1.45
Mean	47.96	6.3	0.089	2.018	15.94	0.26
Min	41.80	-13.0	-0.637	1.850	10.68	-0.57
Std. Error (n=943)	0.064	0.08	0.0216	0.0014	0.034	0.011

Table 4.4.1: The maximum and minimum values seen for each of the measured variables during the Ashes series from the spin bowler to all five batsmen.

A bowling machine must therefore be able to release deliveries with speeds of between 59.60mph and 41.80mph at a launch angle of between 13.9 degrees and -13.0 degrees, from a position of 1.609 metres wide of centre stump to -0.637 metres wide of centre stump and a height of between 2.523 metres and 1.850 metres if it is able to replicate the performance of this bowler. These are of course the extreme values seen and more focus should be placed upon matching the consistency seen within each delivery type from the spin bowler, however any bowling machine must still be able to move to these positions and release deliveries at the quoted speeds and launch angles if it is to truly represent a bowler's complete performance.

The maximum and minimum values seen for deliveries bowled by the elite fast bowler throughout the Ashes series to all five batsmen are summarised in figure 4.4.2.

Fast Bowler: All Batsmen						
	Release Speed	Launch Angle	Release Width	Release Height	Pitching Length	Pitching Width
	(mph)	(degrees from horizontal)	(metres wide of centre stump)	(metres from floor)	(metres from bowler's stumps)	(metres wide of pitch centre line)
Max	99.92	9.9	1.253	2.339	23.15	1.36
Mean	88.23	-1.4	-0.203	2.001	12.71	-0.07
Min	58.68	-9.3	-0.884	1.876	6.68	-0.74
Std. Error (n=624)	0.116	0.07	0.0224	0.0025	0.094	0.016

Table 4.4.2: The maximum and minimum values seen for each of the measured variables during the Ashes series from the fast bowler to all five batsmen.

Perhaps the most surprising data in table 4.4.2 are the maximum and minimum release speeds seen for the fast bowler. A difference of 41.24 mph between the fastest and slowest deliveries witnessed during the Ashes series. It should be noted that the slowest delivery also had the most flighted launch angle of 9.9 degrees above the horizontal plane. This delivery was clearly released with a different technique to the bowler's stock delivery, with the likelihood that the ball was released from the rear of the hand during release resulting in a more flighted launch angle and less speed being imparted onto the ball. This is the most common "slower ball" technique used by fast bowlers.

4.5: Bowling Strategy

The output variables for each delivery variation have been established. A training system may however be required to replicate the strategy of a particular bowler. This would mean releasing deliveries with correct ball flight characteristics in an order that represents a specific player's match strategy. The data displayed in figures 4.2.2 and 4.3.5 gives the likelihood of facing each delivery type from the spin and pace bowler respectively. In order to replicate each bowler's strategy, the order in which these deliveries are released and their pitching position must be considered.

The spin bowler analysed within this chapter demonstrated a use of specific tactics to individual batsmen. These tactics may have been premeditated or a response to the match situation, however this is not something distinguishable from the data alone. It is however possible to pick out differences in approach adopted by bowlers to individual batsmen. One clear example of tactics employed by the bowler is presented in figure 4.5.1, a pitch map of deliveries from the spin bowler to batsmen R2 and R3 during overs 105-151 of the 1st innings in the 2nd Ashes test match.

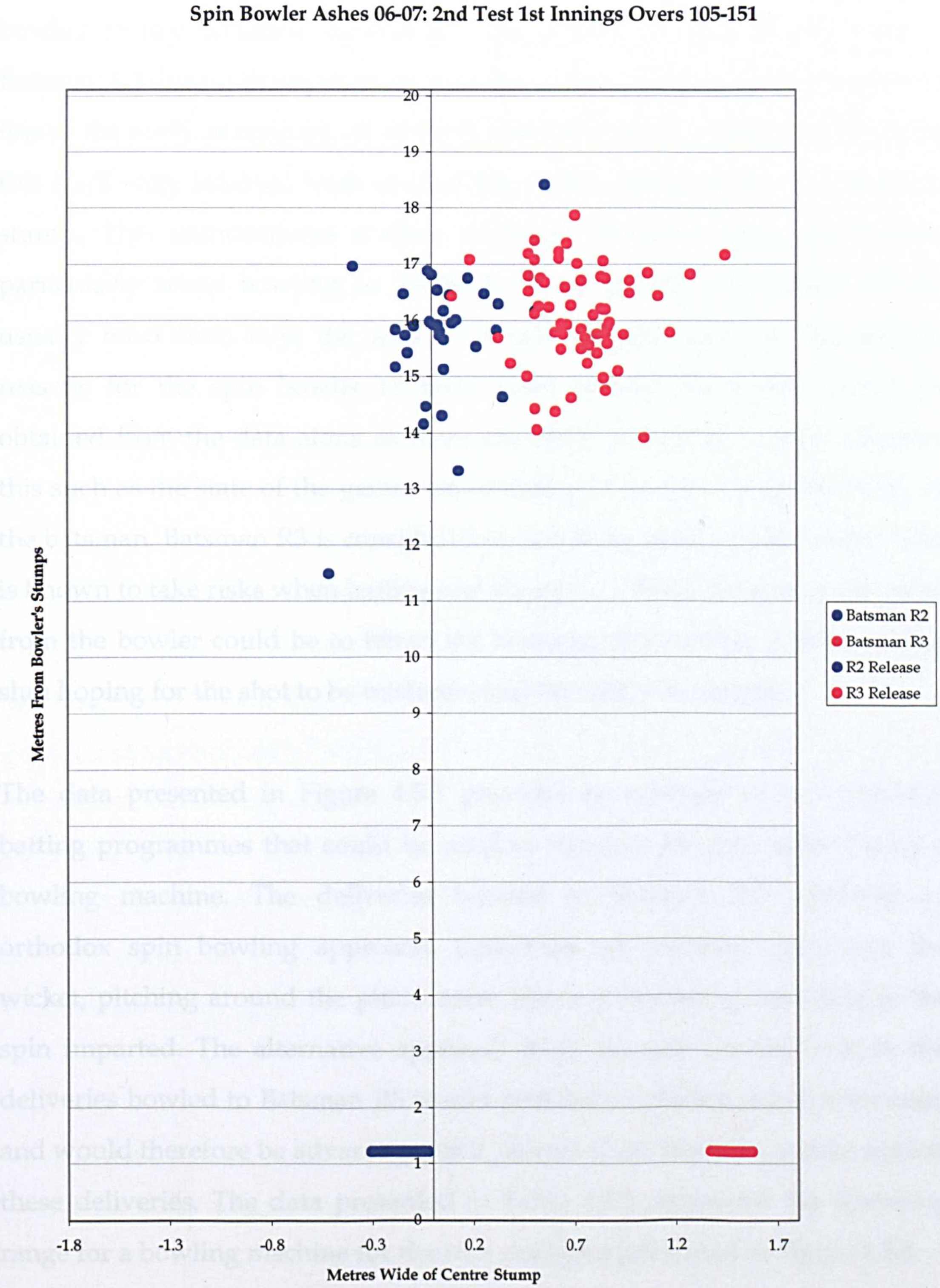


Figure 4.5.1: The release and pitching positions of deliveries bowled by the spin bowler to batsmen R2 and R3 during overs 105-151 of the 1st innings in the 2nd Ashes test match.

During the 46 over period concerned in figure 4.5.1, the spin bowler only bowled to two batsmen, R2 and R3. The bowler released all deliveries to Batsman R2 during this spell from over the wicket, pitching around the centre line of the pitch. In contrast, all of the deliveries bowled to Batsman R3 during this spell were released from around the wicket, pitching on or outside leg stump. This demonstrates a clear adoption of tactics from the bowler, particularly when bowling to Batsman R3 as a right arm bowler would usually bowl from over the wicket to right handed batsmen. The specific reasons for the spin bowler to bowl from around the wicket cannot be obtained from the data alone as there are many factors that could influence this such as the state of the game, the condition of the pitch and the ability of the batsman. Batsman R3 is considered an attacking middle order player who is known to take risks when batting and therefore a likely reason for this tactic from the bowler could be to tempt the batsman into playing a lofted sweep shot hoping for the shot to be mistimed and the ball to be caught.

The data presented in Figure 4.5.1 provides an example of two potential batting programmes that could be used to simulate the two tactics using a bowling machine. The deliveries bowled to Batsmen R2 represent an orthodox spin bowling approach. Deliveries are released from over the wicket, pitching around the pitch centre line and deviating according to the spin imparted. The alternative approach from the spin bowler, seen in the deliveries bowled to Batsman R3 would provide a different test to a batsman and would therefore be advantageous if players were also able to train against these deliveries. The data presented in Table 4.5.1 represents the operating range for a bowling machine for the two strategies presented in Figure 4.5.1.

Spin Bowler: Batting Programmes						
	Release Speed	Launch Angle	Release Width	Release Height	Pitching Length	Pitching Width
R2	(mph)	(degrees from horizontal)	(metres from centre stump)	(metres from floor)	(metres from bowler's stumps)	(metres from centre line)
Max	49.83	10.9	-0.02	2.52	18.42	0.98
Mean	45.58	5.7	-0.16	2.05	15.72	0.05
Min	42.62	0.0	-0.31	1.97	11.49	-0.94
Std Error (n=34)	0.281	0.42	0.013	0.016	0.209	0.073
R3						
Max	49.37	9.9	1.58	2.06	17.87	1.45
Mean	46.37	5.5	1.48	2.01	16.09	0.73
Min	43.56	0.0	1.37	1.95	13.92	0.10
Std Error (n=62)	0.132	0.28	0.006	0.004	0.111	0.031

Table 4.5.1: The maximum, minimum, mean and standard error in the mean values for each of the measured variables for the deliveries bowled to batsmen R2 and R3 during the 1st innings of the 2nd Ashes test.

If a batsman wished to replay a sequence of deliveries faced in a previous match, the order in which each delivery would be released could be programmed into an automated bowling machine due to the low number of total deliveries in each programme (34 and 62). If, however a batsman wanted to face a large number of representative deliveries then balls could be output in random order with the number of each delivery type reflecting the data presented in figures 4.2.2 and 4.3.5. For example, if a right handed batsman wanted to face a spell from the spin bowler analysed during this chapter from over the wicket then 80% of deliveries should be leg breaks, 13% sliders, 2% flippers and 5% googlys.

A further study was conducted to analyse the pitching positions of deliveries with reference to the number of runs scored. One objective for a new training system outlined by coaches at the ECB would be to bowl consistent deliveries that offer the batsman little opportunity to score runs. Elite level bowlers will often bowl a number of deliveries in succession that restrict the scoring potential of batsmen. The aim of this tactic is to frustrate the batsman and force him into playing an attacking shot to a delivery that he would usually defend. Figure 4.5.2 is a pitch map presenting mean pitching positions of deliveries from the spin bowler relative to the number of runs scored from them. Error bars represent the standard error in the mean.

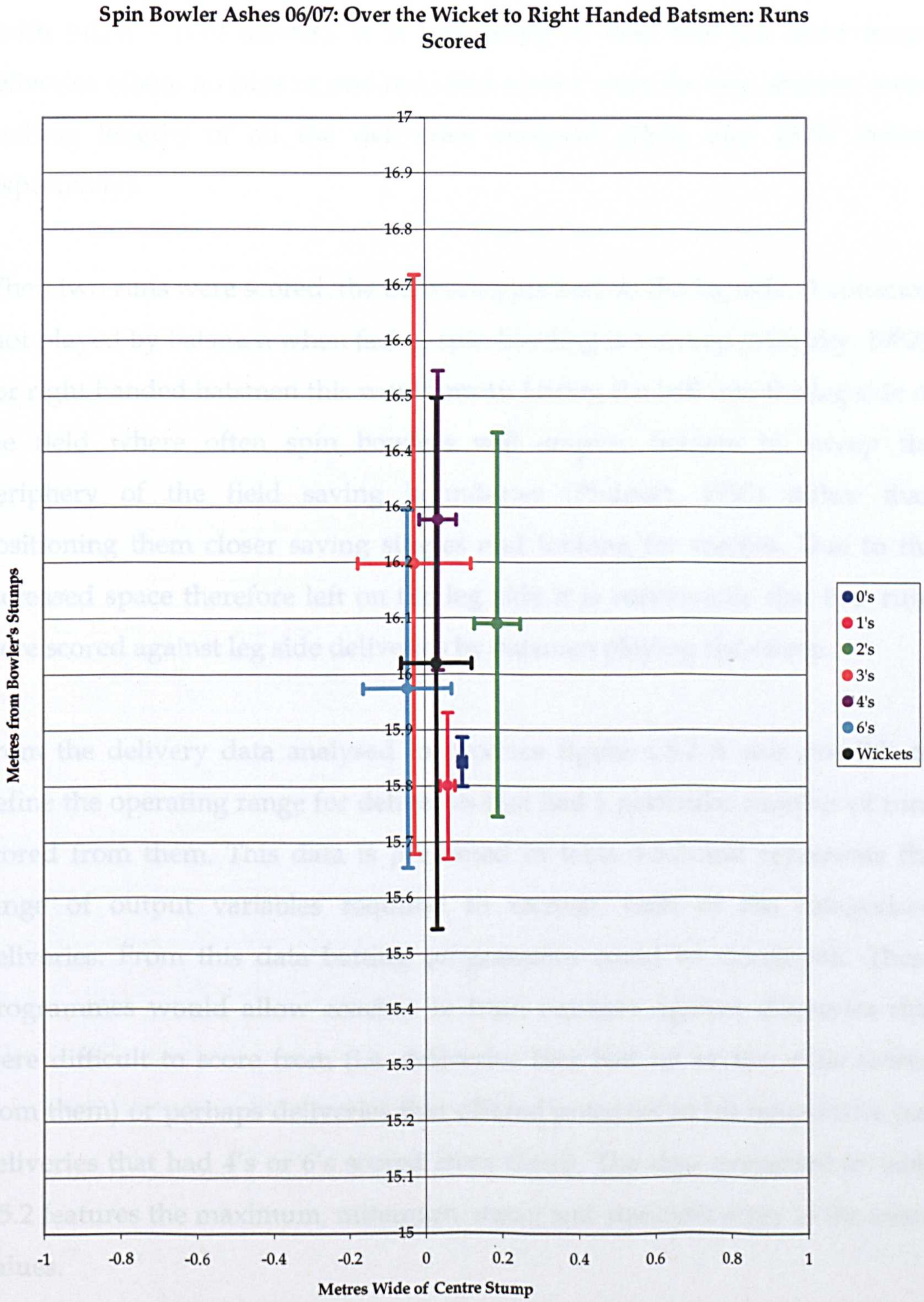


Figure 4.5.2: The mean pitching positions of deliveries with runs scored against them.

The data presented in figure 4.5.2 demonstrates the consistency of the elite spin bowler. The mean pitching position of the analysed deliveries fell within 0.50 metres of each other in length (15.80 - 16.28 metres) and 0.24 metres in width (-0.05 - 0.19 metres). It is interesting to note that the most frugal deliveries where no runs or one run were scored were the two shortest mean pitching lengths of all the deliveries analysed (15.84 and 15.80 metres respectively).

When two runs were scored, the deliveries pitched on the leg side. A common shot played by batsmen when facing spin bowling is a sweep (Murphy, 1982). For right handed batsmen this would mean hitting the ball into the leg side of the field where often spin bowlers will employ fielders to sweep the periphery of the field saving boundaries (Philpott, 1995) rather than positioning them closer saving singles and looking for catches. Due to the increased space therefore left on the leg side it is conceivable that two runs were scored against leg side deliveries by batsmen playing the sweep.

From the delivery data analysed to produce figure 4.5.2 it was possible to define the operating range for deliveries that had a particular number of runs scored from them. This data is presented in table 4.5.2 and represents the range of output variables required to recreate each of the categorised deliveries. From this data batting programmes could be developed. These programmes would allow coaches to train batsmen against deliveries that were difficult to score from (i.e. deliveries that had no or few runs scored from them) or perhaps deliveries that offered potential to hit boundaries (i.e. deliveries that had 4's or 6's scored from them). The data presented in table 4.5.2 features the maximum, minimum, mean and standard error in the mean values.

Spin Bowler: Runs Conceded						
	Release Speed (mph)	Launch Angle (degrees from horizontal)	Release Width (metres from centre stump)	Release Height (metres from floor)	Pitching Length (metres from bowler's stumps)	Pitching Width (metres from centre line)
0's						
Max	59.62	12.8	0.19	2.22	18.46	0.82
Mean	48.06	6.4	-0.23	2.02	15.84	0.10
Min	41.8	-9.5	-0.63	1.92	10.68	-0.57
Std Error (n=453)	0.093	0.12	0.008	0.002	0.044	0.011
1's						
Max	58.75	13.1	0.07	2.52	19.70	0.69
Mean	48.18	7.0	-0.23	2.02	15.80	0.06
Min	42.25	-13.0	-0.64	1.89	10.90	-0.33
Std Error (n=117)	0.201	0.29	0.017	0.006	0.131	0.020
2's						
Max	50.66	11.6	0.03	2.15	18.44	0.59
Mean	47.88	6.8	-0.19	2.01	16.09	0.19
Min	43.43	-3.4	-0.50	1.92	12.52	-0.40
Std Error (n=19)	0.519	0.8	0.041	0.013	0.344	0.060
3's						
Max	49.06	7.4	-0.15	2.17	17.21	0.35
Mean	48.13	5.2	-0.26	2.04	16.20	-0.03
Min	45.44	1.2	-0.50	1.96	15.10	-0.20
Std Error (n=4)	1.039	1.62	0.092	0.055	0.520	0.148
4's						
Max	57.24	13.9	0.00	2.09	18.73	0.55
Mean	47.84	6.7	-0.23	2.01	16.28	0.03
Min	43.76	-1.3	-0.57	1.94	12.00	-0.55
Std Error (n=37)	0.388	0.48	0.028	0.006	0.269	0.049
6's						
Max	50.96	11.3	-0.05	2.06	16.68	0.17
Mean	48.25	8.9	-0.25	2.02	15.97	-0.05
Min	44.64	7.5	-0.60	1.97	15.33	-0.44
Std Error (n=5)	1.265	0.76	0.107	0.021	0.320	0.116
Wickets						
Max	49.55	10.6	-0.03	2.01	17.03	0.33
Mean	47.46	8.3	-0.19	2.00	16.02	0.03
Min	45.27	6.0	-0.50	1.97	14.72	-0.13
Std Error (n=5)	0.888	0.8	0.098	0.008	0.477	0.092

Table 4.5.2: The maximum, minimum, mean and standard error in the mean values for each of the measured variables for deliveries bowled to right handed batsmen from over the wicket.

The data presented in table 4.5.2 provides the operating range of output variables for each of the potential batting programmes. The data does not however provide information pertaining to ball type and the number of each ball type required to represent the strategy of the spin bowler. To obtain this data, the number of each ball type has been calculated as a percentage of the total number of deliveries for each "runs scored" programme. This data is presented in table 4.5.3.

Runs Scored	Leg Break	Slider	Flipper	Googly
(Total Deliveries)	%	%	%	%
0's (453)	83.7	9.7	1.5	5.1
1's (117)	76.9	17.9	2.6	2.6
2's (19)	63.2	31.6	0	5.2
3's (4)	100	0	0	0
4's (37)	56.8	24.3	5.4	13.5
6's (5)	80	20	0	0
Wickets (5)	80	20	0	0

Table 4.5.3: The percentage of each delivery type to be bowled for each of the "runs scored" batting programmes.

If a batsman were to face a programme of deliveries aimed at restricting his scoring potential, deliveries would be derived from the "0's" batting programme. Of the total number of deliveries he would face, 83.7% would be leg breaks, 9.7% sliders, 1.5% flippers and 5.1% googlys. The range of output variables would be derived from the "0's" range presented in table 4.5.2.

4.6: Conclusions

The research presented within this chapter has analysed the performance of two elite bowlers throughout a test series. The analysis supplements the knowledge gained though high speed video analysis seen in Chapter 3 with ball flight data from elite match play. A range of output variables have been developed forming the operating range for a bowling machine tasked with replicating elite performance. Additionally the deliveries have been categorised into ball type for the spin bowler and pitching length for the pace bowler. Combining this data will allow batting programmes to be developed with deliveries being released with correct output variables in a number that represents the strategy of the bowler analysed.

The strategy of the elite spin bowler has been analysed in this Chapter. Firstly focussing upon a specific match scenario where individual tactics were employed to two batsmen. Secondly, deliveries were analysed with respect to the number of runs scored from them. These data would allow bowling machine programmes to be developed that could test batsmen by restricting scoring opportunities or potentially offering them the opportunity to hit boundaries. These data would additionally allow batsmen the opportunity to face each of the bowler's wicket taking deliveries from the Ashes series.

5: Cricket Batting Analysis

The research described in this chapter is focused upon determining differences in the movement patterns of a premier league club cricketer when facing a human bowler and a typical bowling machine. The aim of this study was to see whether there were differences in the timing of movements of the batsman when faced with the two different training scenarios. Whilst there is no doubting the benefit of using current bowling machines (see Chapter 2) to teach and practice the technique of particular shots, they do not currently provide batsmen with relevant pre-release information (i.e. batting cues) about approaching deliveries, neither do they add to the memory store of previously faced deliveries available to batsmen. From the results of this work it has been possible to make initial judgements on the validity of using bowling machines to train for match scenarios.

While there have been previous studies conducted in this area, notably Gibson and Adams (1989, see Chapter 2, section 2.5), it was felt that with highly accurate, modern equipment available such as a number of high-speed video cameras offering a high image resolution, the HawkEye ball tracking system and a realistic training environment for testing to be conducted within, additional knowledge could be developed within this area of research addressing the following questions:

- What are the differences in the timing of events during the batting stroke and foot movement when a batsman faces deliveries from a human bowler and a bowling machine?

- What are the differences in visual information available to a batsman when faced with these two delivery methods?

- How easily are human deliveries recreated using currently available bowling machines?

5.1: Experimental Method

Player testing was conducted at the ECB National Cricket Centre, Loughborough. An amateur batsman, who plays for a premier league club side was filmed batting against a non-familiar human bowler of the same standard and a BOLA bowling machine. Note: The novel bowling machine that is the main subject of the research in this thesis was not used in these trials due to the difficulties in transporting and locating the equipment to the NCC and the lack of ready available power in the playing arena. The movements of both the batsman and bowler/bowling machine operator were recorded from the initiation of the bowler's run up/machine operator's signal to the completion of the batsman's shot. The batsman was filmed from both a front on and side on perspective and the bowler/bowling machine was filmed from a front on perspective (see figure 5.1.1). The cameras were synchronised and recording was initiated using an 5 volt TTL trigger when the bowler or bowling machine operator broke a laser beam positioned at the beginning of the run up (or machine operator signal) respectively.

For the deliveries produced by the bowling machine, recording was initiated when the bowling machine operator broke a laser beam when signalling an imminent delivery to the batsman by raising his arm. A specifically designed protective camera shield was assembled to house two high-speed video cameras, one focussed upon the batsman, the second focussed upon the bowler, both from a front on perspective. The shield was positioned in the centre of the designated pitch at a distance of 6 metres from the stumps at the bowler's end. Both cameras were Photron SA1 High Speed Video Cameras (Photron, 2007). The cameras were set up to sample at 500 frames per second which enabled data to be recorded at resolution of 1024 x 1024 pixels. Note:

higher sample rates require a reduced resolution (i.e. 512 x 512 pixels). A third high speed camera was positioned orthogonally to the pitch, in line with the batsman's crease on a standard Manfrotto tripod at a height of 1.2 m, focussed upon the batsman. This camera was a Photron Ultima APX high-speed video camera which also sampled at 500 fps at a resolution of 1024 x 1024 pixels. A CAD generated image of the equipment setup used for this pilot study is illustrated in figure 5.1.1.

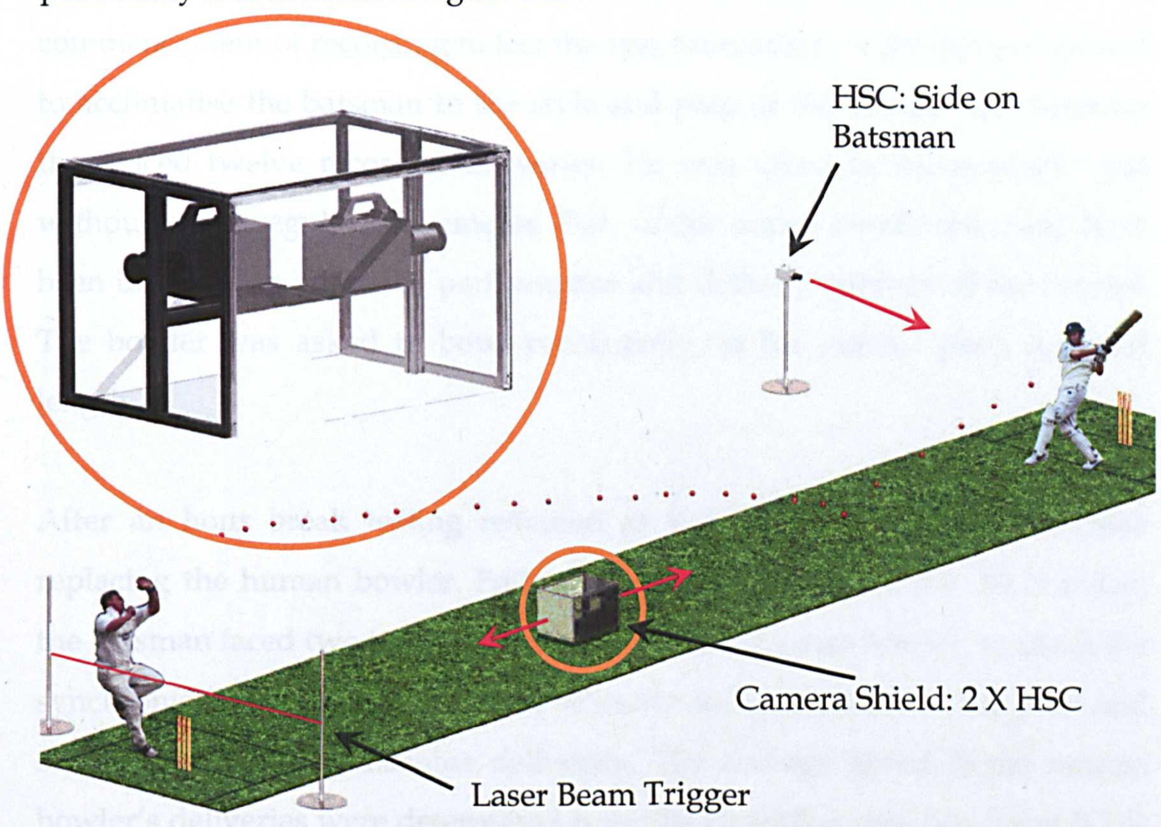


Figure 5.1.1: Batsman Performance Test Equipment Setup.

Additional data (e.g. release speed, pitching position) was recorded for each delivery using the HawkEye system (see Chapter 3, section 3.2.7). HawkEye is a computer based ball tracking system that uses three orthogonal cameras recording at 140 frames per second to capture the trajectory of the ball before and after it bounces. Mathematical algorithms are then used to predict the complete ball trajectory. These data enabled the ball flight characteristics of the deliveries bowled to be quantified and were used to provide a classification of each delivery faced by the batsman when facing the real bowler and the bowling machine. Hence timing performance could be determined for similar types of deliveries.

5.2: Experimental Procedure

The batsman was allowed a short period (i.e. 10 minutes) to warm up and then faced two trial deliveries from the human bowler prior to the commencement of recording to test the synchronisation of the equipment and to acclimatise the batsman to the style and pace of the bowler. The batsman then faced twelve recorded deliveries. He was asked to bat normally and without any irregular movements that, under match conditions, may have been intended to affect the performance and delivery strategy of the bowler. The bowler was asked to bowl consistently, at his normal pace, line and length.

After an hour break testing resumed as before with a bowling machine replacing the human bowler. Following a warm up period (i.e. 10 minutes) the batsman faced two trial deliveries, as with the human bowler, to check the synchronisation of equipment and to allow acclimatisation to the pace and style of the bowling machine deliveries. The average speed of the human bowler's deliveries were determined from the HawkEye data (see Table 5.3.3) and the bowling machine was set to replicate this. The bowling machine operator warned the batsman of an imminent delivery by raising his hand with the ball prior to inserting it into the machine, this is the most commonly used method adopted by coaches. Between deliveries, the angle of the head of the bowling machine was marginally altered (± 2 degrees) in an attempt to reproduce some of the variability in length seen in human bowling, without any short balls or yorkers. The line of the deliveries was kept consistent on the stumps.

5.3: Results

Since each of the video cameras sampled at 500 fps each frame equated to 0.002 s. It was therefore possible to establish the timings of events during each ball faced ± 0.001 s. Mean times were calculated for each *event* (e.g. bat back lift, front foot up) during the batting stroke, and the mean times for foot movements were also recorded. A series of still images taken from the front and side on high speed footage of the batsman during the study at six key points identified during the batting stroke are illustrated in figure 6.3.1.

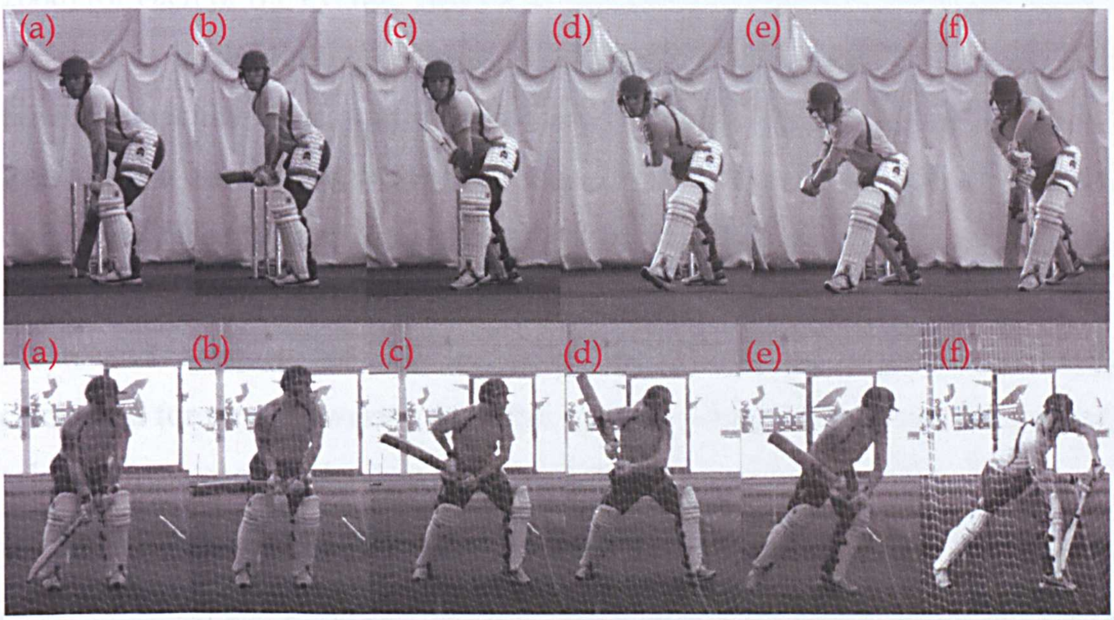


Figure 5.3.1: Still images taken from the high speed video of the batsman from both front and side on at six key positions during the batting stroke; (a) Bat back lift, (b) Bat held level, (c) Movement upwards, (d) Bat reaches top of backswing, (e) Movement down, (f) Bat and ball contact.

These six "events" were identified from the work of Gibson and Adams (1989), however, due to differences in player technique, alterations were made to accommodate the batsman's individual movements. The mean times for each of the events during the batting stroke with respect to ball release (i.e. time t=0) for all of the deliveries faced from a human bowler and a bowling machine are displayed in Table 5.3.1. The events are chronologically ordered. The point of release was considered to be the first frame in which the bowler no longer had contact with the ball or the moment the ball emerged from the "mouth" of the bowling machine, examples of these points can be seen in figure 5.3.2.

On the occasions that there was no bat and ball contact made then the frame in which the ball was level with the batsman's bottom hand was assumed to be representative of a time when a point of contact would have been made. The sixth column of Table 5.3.1 presents the calculated t-values (Coolidge, 2000) for each of the events. This value indicates whether there are significant differences in the timing of events when the batsman faces the bowler and bowling machine. It should be noted that against the bowling machine there was only a secondary front foot movement seen on nine of the twelve deliveries faced. When facing the bowler, the batsman had a secondary movement of the front foot on all twelve of the deliveries faced. Thus the mean and t-values for the secondary front foot movement have been calculated for nine deliveries, with the corresponding delivery numbers being selected from each of the data sets for analysis.

Event	Bowling Machine:	Standard Error In Mean	Bowler:	Standard Error In Mean	Time Difference:	T-Test Value:
	±0.002s		±0.002s		±0.002s	
Bat Back Lift	-0.999	±0.0660	-0.838	±0.0423	0.161	2.141*
Bat Held Level	-0.474	±0.0579	-0.328	±0.0425	0.146	2.118
Movement Upwards	-0.176	±0.0499	-0.068	±0.0490	0.108	1.609
Front Foot Uplift	-0.002	±0.0253	-0.152	±0.0109	0.150	5.675*
Front Foot Down	0.229	±0.0428	0.056	±0.0065	0.188	4.520*
Secondary Foot Movement Up	0.244	±0.0232	0.283	±0.0232	0.054	-1.667
Bat Top of Backswing	0.385	±0.0096	0.398	±0.0183	0.013	0.654
Movement Down	0.418	±0.0107	0.436	±0.0215	0.018	0.779
Secondary Foot Movement Down	0.455	±0.0176	0.685	±0.0982	0.230	-2.081
Bat and Ball Contact	0.620	±0.0025	0.637	±0.0089	0.017	-1.912

Table 5.3.1: The mean times, in seconds, of specified events during the batting stroke with respect to ball release by a bowler or bowling machine. * Denotes a significant difference between the two sets of data. Critical t: (22df, two tailed, a of 0.05) = ±2.074, (16df, two tailed, a of 0.05) = ± 2.120.

There are significant differences in the timings of the batsman's bat back lift, front foot uplift and front foot down movements when facing a bowler and a bowling machine. Against a bowling machine the batsman's bat back lift was significantly earlier than against a bowler (0.161 s). His front foot movement, both up and down was significantly later (0.150 s and 0.173 s respectively) against a bowling machine than against a bowler. Once the front foot has been planted, there is little difference in the timings of the batsman's movements (i.e. max 0.039 s difference) until bat and ball contact. The discrepancy between the values for secondary movement down of the front foot can be explained by the fact that on two occasions, when facing deliveries from the human bowler, the batsman played shots with only his back leg on the ground and only planted his front foot once he had played the shot.

The timing of events during the operation of the bowling machine and the delivery stride of the human bowler are displayed in Table 5.3.2. The timings are all relative to the ball release event.

Event	Bowling Machine	Standard Error In Mean	Event	Bowler	Standard Error In Mean
	±0.002s	±		±0.002s	±
			Bound:	-0.697	0.004
Arm Movement:	-1.131	0.035	Rear Foot Impact:	-0.319	0.006
Signal:	-0.680	0.049	Front Foot Impact:	-0.132	0.002
Ball Release:	0.000	0.000	Ball Release:	0.000	0.000
Ball Bounce:	0.563	0.005	Ball Bounce:	0.438	0.029

Table 5.3.2: The mean times, in seconds, of specified events during the operation of the bowling machine and run up and delivery stride of the human bowler during testing with respect to ball release.

There is increased variation in the times of events for the operation of the bowling machine (e.g. signal σ_m = 0.049 s) than the delivery stride of the human bowler (e.g. bound: σ_m = 0.004 s). The initiation of arm movement upwards by the bowling machine operator commenced, on average, 1.131 s before the ball was released. In contrast to this, the human bowler began the bound of the delivery stride 0.697 s prior to releasing the ball.

A series of still images of both the human bowler and the operation of the bowling machine from a batsman's perspective, taken at key points during the delivery stride and operation of the machine respectively, are illustrated in figure 5.3.2. The images have been arranged sequentially with respect to the ball release position. It should be noted that there are only three images for the bowling machine. This is because there was no discernable difference between the signal and release stages from the batsman's perspective.

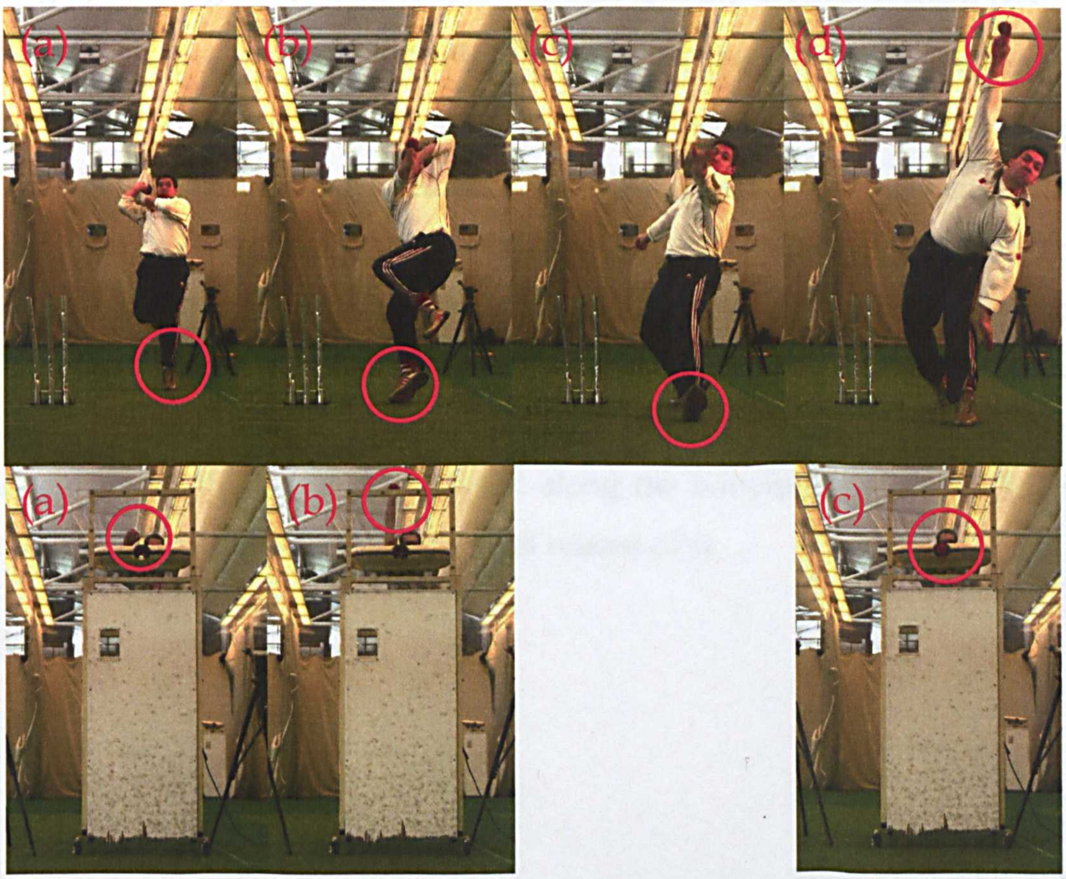


Figure 5.3.2: The visual information available to the batsman. Top: (a) The Bound, (b) Rear foot impact, (c) Front foot impact, (d) Release. Bottom: (a) Initiation of arm movement, (b) Signal to batsman, (c) Release.

The data displayed in Table 5.3.3 are the mean values for the ball flight characteristics of the deliveries bowled by both the human bowler and the bowling machine derived from the Hawkeye data. The data are concerned with the release and pitching position of the deliveries and their release speed.

Delivery Feature	Bowling Machine	Standard Error in Mean	Bowler	Standard Error in Mean	T-Test Value
Release Wide of Centre Stump	-0.324	±0.0227	-0.566	±0.0408	5.136*
Release Height	2.050	±0.0294	2.010	±0.0340	2.010
Release Speed (mph)	66.964	±0.4417	67.750	±0.5072	1.385
Pitching Wide of Centre Stump	-0.151	±0.0502	-0.560	±0.0422	5.590*
Pitching Length from Bowlers Stumps	16.880	±0.1674	12.152	±0.4565	-11.333*

Table 5.3.3: Mean values of features of deliveries bowled by the human bowler and bowling machine. Features are measured in metres unless stated, negative values indicate distances to the left of centre stump. * Denotes a significant difference between the two sets of data. Critical t: (22df, two tailed, a of 0.05) = ±2.074.

A simplified timeline of events is presented in figure 5.3.3. The mean timings of the batsman's bat and front foot movements are plotted alongside the mean timings of movements of the bowler or bowling machine operator. The movements of the batsman when facing the bowling machine and the movements of the bowling machine operator are plotted along the top of figure 5.3.3. The movements of the batsman when facing the bowler and the movements of the bowler are plotted along the bottom of figure 5.3.3. The times plotted are all with respect to ball release (0 s).

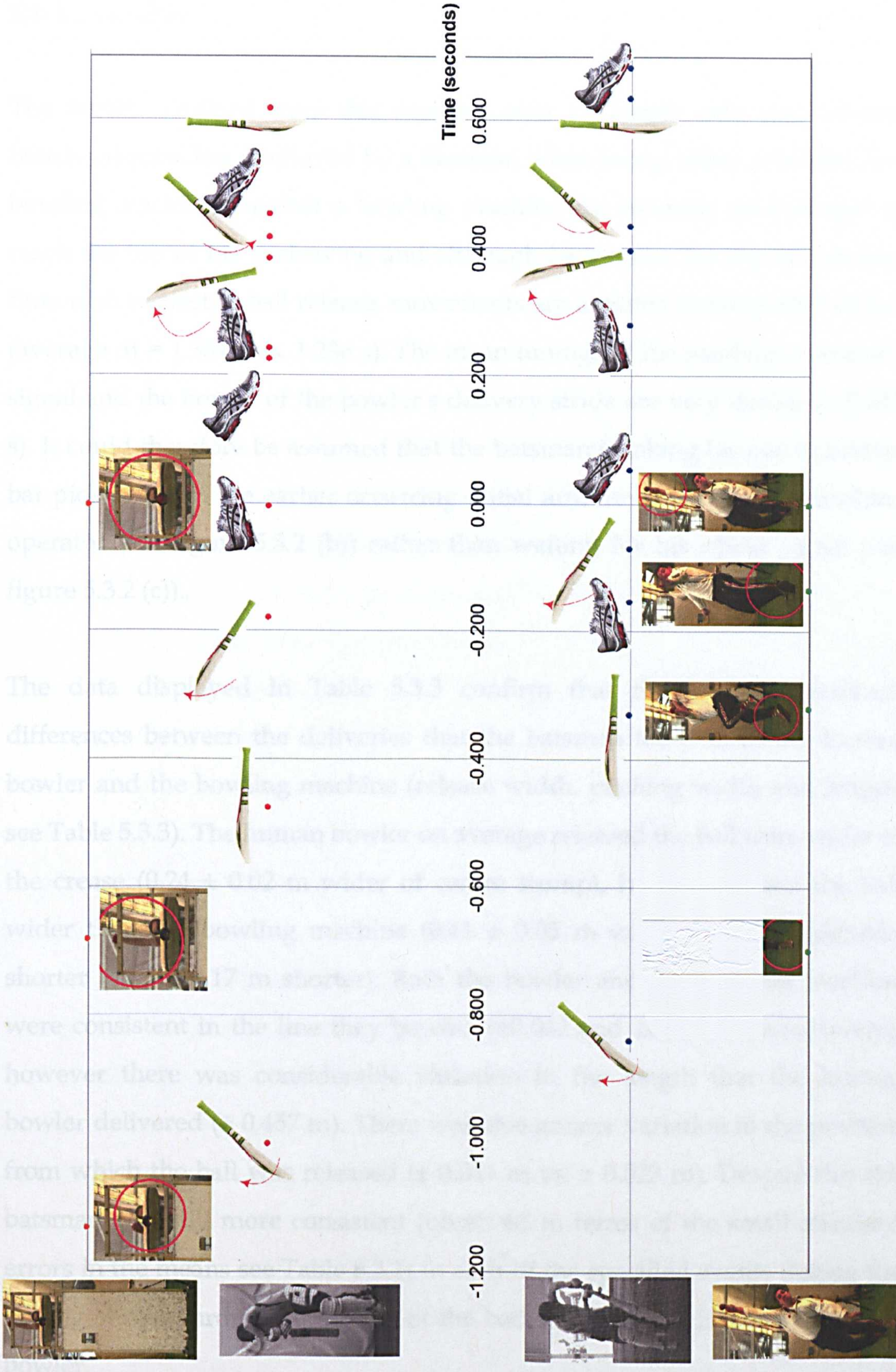


Figure 5.3.3: The mean timing of events during the batting stroke when the batsman faced the bowling machine (top) and human bowler (bottom).

5.4: Discussion

The results obtained from this research offer an insight into the different batting approaches employed by a batsman when facing either a bowler or a bowling machine. Against a bowling machine the batsman takes longer to reach the top of his backswing and although he reaches the top at a similar time with respect to ball release, movements are initiated considerably earlier (average $\Delta t = 1.384$ s vs. 1.236 s). The mean timings of the machine operator's signal and the bound of the bowler's delivery stride are very similar (± 0.017 s). It could therefore be assumed that the batsman is taking his cue to initiate bat pick up from the earlier occurring initial arm movement of the machine operator (see figure 5.3.2 (b)) rather than waiting for his *official* signal (see figure 5.3.2 (c)).

The data displayed in Table 5.3.3 confirm that there were significant differences between the deliveries that the batsman faced from the human bowler and the bowling machine (release width, pitching width and length, see Table 5.3.3). The human bowler on average released the ball from wider in the crease (0.24 ± 0.02 m wider of centre stump), he also pitched the ball wider than the bowling machine (0.41 ± 0.05 m wider) and considerably shorter (4.73 ± 0.17 m shorter). Both the bowler and the bowling machine were consistent in the line they bowled (±0.042 and ±0.050 m respectively), however there was considerable variation in the length that the human bowler delivered (± 0.457 m). There was also greater variation in the position from which the ball was released (± 0.041 m vs. ± 0.023 m). Despite this the batsman was still more consistent (observed in terms of the small standard errors in the means see Table 5.3.1) in each of the specified events during the batting stroke, through to the top of the backswing, when facing the human bowler.

The batsman commented after the test that he felt he was waiting at the top of his backswing in anticipation of the ball being released by the bowling machine. This is reflected in the earlier pick up of his bat and the prolonged time it took him to reach the top of his backswing in contrast to facing the human bowler. A comparison of the visual information available between each scenario from a batsman's perspective can be seen in figure 5.3.2.

One of the clearest indicators of pre-release information being used by the batsman is the consistently earlier movement of the front foot when facing the human bowler. The technique, observed by most batsmen is to move the front foot forward, towards the bounce of the ball if it is a full delivery, or to move the feet backwards if the delivery is short. For the batsman to be moving his feet before the ball has been released, implies that he must be interpreting information received from the movements of the bowler and predicting the length of the imminent delivery.

When facing the bowling machine, the batsman's foot movements appear to reflect a lack of pre-delivery information. The data presented in figure 5.3.3 confirms that the *front foot* does not *move* until the ball has been released, suggesting that there was no information available to make a delivery length judgement from. In contrast, however, the *front foot* is *planted* earlier when facing the bowling machine than when facing the human bowler. One explanation for this could be that due to the consistency of the deliveries output by the bowling machine, the batsman is anticipating the length of the delivery based upon the previous deliveries faced.

5.5: Conclusions

It is clear that there is a need to conduct this testing with a larger player sample of varying standards before it would be possible to form a clear judgement on the differences observed in players batting against a human bowler and a bowling machine. It is however possible to conclude from this initial research study, in agreement with previous research conducted in Australia by Gibson and Adams (1989, see Chapter 2, section 2.5) that there appears to be a different approach adopted by batsmen when facing bowling machines to that seen against human bowlers in that the differences in stroke timing suggest that the tasks vary in the use of spatial and temporal information available to the batsman. It would appear that the batsman initiates the stroke based upon temporal cues and then modifies it as a result of additional temporal and spatial information (Gibson and Adams, 1989).

The results of this study do however differ from those presented by Gibson and Adams (1989). Their findings concluded that the batsman moved his bat upward significantly later and his front foot significantly earlier when facing a bowling machine than a human bowler. They attributed the late bat movement to a lack of information when facing a bowling machine compared to a bowler. Premeditation of delivery length is recognised as the reason for early foot movement, with the angle of the bowling machine head a clear indicator of the next delivery's length. The case study described in this chapter, however, found that the batsman picked his bat up earlier and moved his front foot later against a bowling machine. One explanation for this could be that the batsman is taking his cue to pick his bat up from the motions of the bowling machine operator prior to being issued with a signal denoting an imminent delivery. Batsmen move their feet to reposition themselves for a shot according to the line and length of a delivery (Chappell, 2004). The later movement of the front foot suggests that information pertaining to delivery length became available at a later point than against the human bowler. The foot was only moved after the point of ball release suggesting that ball flight information was critical in judging delivery length.

Previous research has concluded that highly skilled batsmen show a unique capability to pick up early information about an oncoming delivery (Muller, 2006). This could be an explanation for the difference in results between the case study described in this chapter and the work of Gibson and Adams (1989). The batsmen analysed here was a skilled amateur player while Gibson and Adams' work was conducted with an Australian International. This could present an alternative reason for the discrepancy in results: the higher skilled international player was greater attuned to the delivery length information available from the bowling machine than the amateur and was therefore able to move his foot earlier. The later bat pick up by the highly skilled player when facing the bowling machine suggests that he used alternative information to the amateur in this study who appears to have reacted to the initiation of arm movement from the bowling machine operator.

It is thus important that further work should include the testing of players of different abilities. Results may allude to the importance of visual cues to higher skilled players with the hypothesis that *"more experienced players are more reliant on earlier visual cues to interpret an imminent delivery"*. When facing the bowling machine they will gain information later and therefore have to react more quickly since delivery information is only available post release. Further to this it would be of benefit to monitor the batsmen's eye movements from the start of the bowler's run up to the point of bat and ball contact either through the use of an eye tracking system or a screen based test in order to determine the focus of his attention throughout the delivery and hence determine the relevance of appropriate visual cues on batting performance and shot selection. The video data has proved that there are clear differences in the visual information available to batsmen when presented with the two delivery methods, however until a study is conducted to compare the areas of visual focus of a batsman for both scenarios ascertaining where information is gained, it is difficult to quantify these differences.

One issue that the study has highlighted is the difficulty coaches face in recreating realistic deliveries using currently available bowling machines. The data presented in Table 5.3.3 confirm this with significant differences seen between the release width and pitching position values recorded for the bowling machine and human deliveries. The bowling machine was operated by an ECB qualified cricket coach trying to recreate the deliveries bowled by the human bowler, however the data proves that this was difficult. Further work conducted in this area should look to use a bowling machine that is easier for the operator to control and thus release deliveries closer to those bowled by humans.

6: Bowling Machine Development

The research work conducted in Chapters 3, 4 and 5 has developed an understanding of the performance criteria necessary for any cricket bowling machine to meet if it is to replicate elite human performance. These performance criteria were established through the combination of a high-speed video analysis of deliveries released by elite cricket bowlers in a training environment (Chapter 3) and a statistical analysis of deliveries bowled by elite players throughout an Ashes test series (Chapter 4). This information was supplemented with an analysis of batting technique when facing a human bowler and a bowling machine (Chapter 5).

The orthogonal high-speed video analysis of deliveries conducted in Chapter 3 enabled parameters to be set for each of the required ball flight characteristics. A range of delivery types from both pace and spin bowlers were recorded and maximum and minimum values were established for each of the required variables. These values form the performance range that a bowling machine must operate within if it is to replicate the deliveries witnessed during player testing.

To complement the data captured during player testing it was important to study the performance of elite bowlers during match-play. HawkEye ball tracking data was used to quantify the deliveries bowled by two bowlers during the 2006/7 Ashes test series. In addition to extra ball flight characteristic data, this study provided an insight into the strategies adopted by bowlers during matches, information that could be used to develop batting programmes for players wishing to practice against a likely delivery sequence from a potential opponent.

The research presented in Chapter 5 described a case study conducted to measure any differences seen between a batsman's technique when facing an unknown human bowler and a currently available cricket bowling machine (BOLA). It is clear that judgement cannot be formed from the results of one case study alone, however the fundamental differences in approach adopted by the batsman when faced with the two scenarios suggests they are two disparate tests for a player. From the results of this trial it is clear that when facing a bowler there are more relevant visual stimuli available to predict an oncoming delivery. Previous research highlights the importance of these stimuli an effective cricket training system should provide a batsmen with these.

The importance of establishing the minimum performance requirements to replicate elite human bowling and provide batsmen with as many match realistic stimuli as possible has been recognised through the research conducted in Chapters 3, 4, and 5. The work presented in this thesis was supported by the England and Wales Cricket Board with the aim of developing a novel cricket bowling machine. The research presented in this thesis commenced during the final testing and evaluation phase of a prototype bowling machine developed at Loughborough University. This machine, as reviewed later in this Chapter, performed to a high standard in terms of imparting speed and spin onto a cricket ball, however there were limitations in the machine design, notably in the spin imparting head that could potentially compromise the health and safety of those operating and facing such a machine.

The research presented in this Chapter therefore follows the development of a second generation bowling machine designed to release cricket bowling deliveries with realistic ball flight characteristics seen in elite bowling (see Chapters 3 and 4). The commercial nature of such a project placed constraints upon the time available for delivery and hence the development of the machine was carried out in conjunction with the human performance analysis studies (Chapters 3, 4 and 5). This is recognised as a limitation of the presented work, as ideally the performance criteria of any machine should be defined prior to design development.

The structure of this Chapter covers a review of the design and performance of a first generation bowling machine and comments on necessary areas of improvement. The design modifications seen in the second generation machine focus upon the spin imparting mechanism. The design will be reviewed and the performance assessed. The ability to impart spin onto the ball in a controlled orientation was established as an important ball flight characteristic during player testing (Chapter 3). The machine will therefore be assessed upon its spin imparting capability and the effect this has on the ball's resultant speed. Throughout the testing period the second generation machine's spin imparting head underwent a series of four design alterations. Each of these iterations is detailed and the resulting impact on machine performance reviewed. In addition, second generation drive wheels have been designed, manufactured and tested and are reviewed with respect to the ability to mimic human bowling performance and the capability of the first generation drive wheels. The following research questions are addressed in this Chapter:

- What are the design features of the first generation prototype machine in need of development?
- What are key design features required in the second generation machine design?
- What is the performance capability of the second generation machine in terms of imparting speed and spin onto a cricket ball?
- How consistent are the deliveries output from the second generation machine?
- How does the performance capability of the second generation machine compare to other currently available ball launching devices?

- What future work is required to complete the development of the second generation bowling machine?

6.1: First Generation Machine:

The first generation bowling machine was a laboratory based prototype designed to determine the feasibility of imparting rifle spin onto a seamed cricket ball. The design of the machine was the result of a series of brainstorming sessions, a qualitative investigation with International players and coaches resulting in a set of Voice of the Customer (VOC) requirements and structured Quality Function Deployment (QFD) analysis whereby each of the existing ball launching machines were evaluated for, amongst other qualities, their ability to create swing, spin, control ball speed and use a real cricket ball.

6.1.1: Machine Design:

The final machine design encompassed a pair of counter-rotating drive wheels used to impart forward velocity onto the ball. The ball travelled from the drive wheels through a barrel into a rotating spin head with inset spring-loaded blades (see figure 6.1.1). These blades protruded into the barrel with an adjustable separation to allow for control over the amount of interaction between the blades and ball (see figure 6.1.2)

To operate the machine, the ball was manually fed between the two counter-rotating wheels and accelerated by the transfer of rotational energy from the wheels onto the ball as a linear velocity. The wheels had a solid hub and a deformable, profiled polyurethane coating. The coating was the contact between the ball and the wheels. The coating's deformable characteristics allowed the separation between the wheels to be set at a shorter distance than a cricket ball's diameter (0.072 m +/- 0.007 m (BS5993:1994)) thus increasing the contact distance between ball and wheels and the concave profile assisting the ball to be output on a consistent path down the barrel.

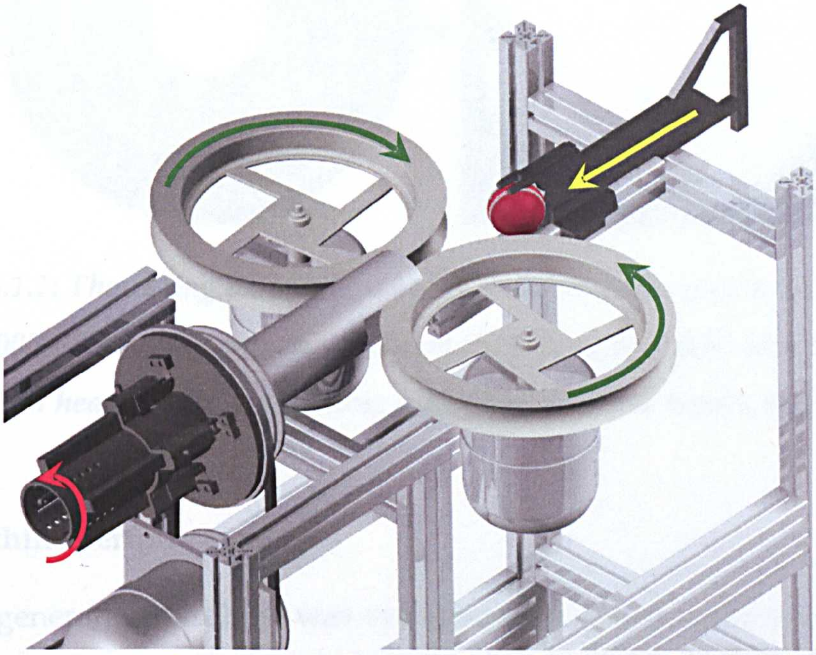


Figure 6.1.1: First generation machine design and operation.

The design of the spin head was derived from rifle theory, where helical grooves are cut into the bore of a gun barrel forming a series of lands (protruding ridges) and grooves (see figure 6.1.2). In a gun the fired projectile interacts with these grooves causing spin around an axis normal to the projectile's direction of motion, gyroscopically stabilising the projectile through the air. The spin head design incorporated straight lands rather than helical, which reduced the spin imparting effect, however straight lands were necessary if the spin head was able to impart spin in both clockwise and anticlockwise directions. The two designs are illustrated in figure 6.1.2, with the standard helical rifling barrel pattern (left) in contrast to the straight blades of the spin head inset into the wall of the rotating barrel (right).

Figure 6.1.2: The rifling principle, as seen looking down a rifle barrel (left) (Doyle, 2005 – www.firearmsid.com) and the rifling principle adapted for the spin head design, as looking down the machine barrel, right.

6.1.2: Machine Performance:

The first generation machine was systematically tested using the Design of Experiments (DoE) approach, where matrices are used to ensure a balanced and focussed set of tests is completed. Six factors were considered when testing within the laboratory: (i) the driving wheel speed and separation, (ii) the spin head attachment speed, (iii) the direction of the spin head attachment, (iv) the blade separation within the spin head, (v) the position of the seam on the ball and (vi) the speed at which the ball was fed into the machine (Justham, 2007).

The first test set out to establish the optimum separation of the counter-rotating drive wheels and the speeds at which the ball was released from the machine using various drive wheels speeds with no interaction from the spin head. Thus for this test the spin head would not be needed and so the blades were set with a separation to match the diameter of the main barrel.

A drive wheel separation of 51 mm was chosen as the optimum as this produced the highest and most consistent ball release speeds (Justham, 2007). The machine was capable of outputting deliveries of up to approximately 43 m/s (96.3 mph) when the drive wheels' speed was at their maximum of 3600 rpm. The machine was therefore confirmed capable of reproducing elite level fast bowling speeds as only four deliveries in International cricket have ever been recorded faster than this (only two of which in matches), with Pakistan fast bowler Shoaib Akhtar's 100.04 mph delivery against New Zealand in Lahore in 2002 the fastest delivery ever recorded (BBC Sport, 2002).

The effect of the spin head on the ball was measured with respect to two key parameters: (i) the amount of spin imparted onto the ball and (ii) the amount of speed the ball lost due to interaction with the spin head. Two blade separations were used (i.e. 72 mm and 66 mm) with five drive wheel speeds (i.e. 500, 900, 1800, 2700 and 3600rpm (see figure 6.1.3)). When calculating the amount of speed lost due to interaction with the blades a simple comparison was made with the speeds achieved when there was no spin head interaction observed using the optimum data from the drive wheel separation testing discussed previously. This comparison showed that the spin head's interaction with the ball reduces the resultant speed of the ball at release by no more than 5% (see figure 6.1.3) (Justham, 2007).

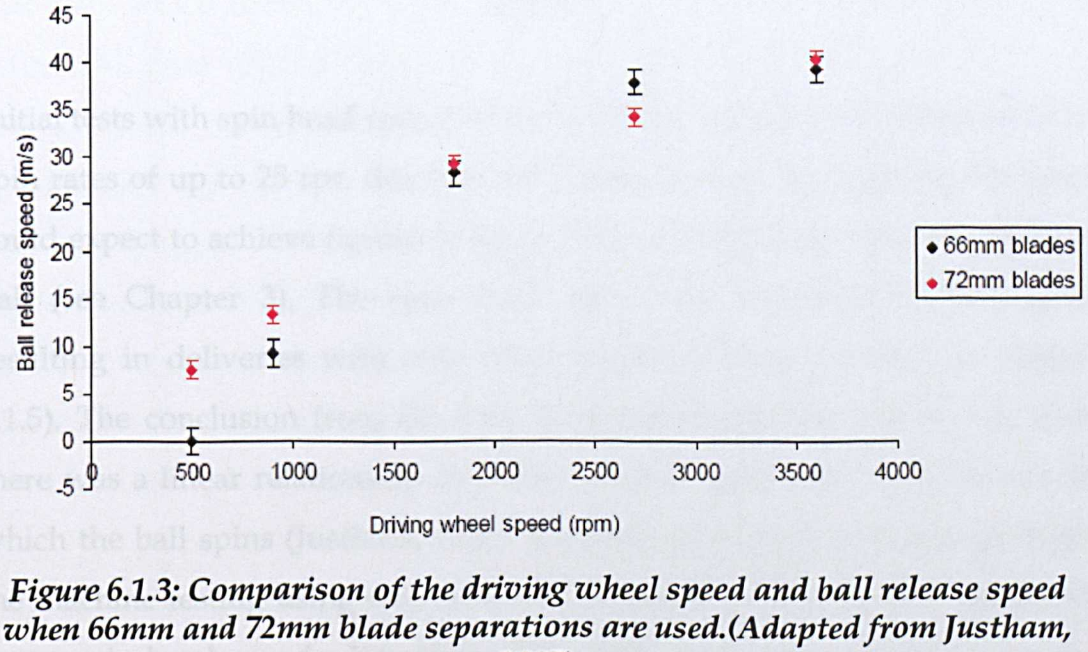


Figure 6.1.3: Comparison of the driving wheel speed and ball release speed when 66mm and 72mm blade separations are used.(Adapted from Justham, 2007)

The effect of the spin head speed on the resultant speed of the ball was measured using a range of drive wheel speeds (500, 900, 1800, 2700 and 3600 rpm). Justham (2007) comments that below 2000 rpm drive wheel speed the ball increases linearly with increased drive wheel speed. However above 2000 rpm the ball speed increases less rapidly. This was attributed to the ball possibly making contact with one wheel before the other, imparting side spin and reducing forward motion energy (see figure 6.1.4).

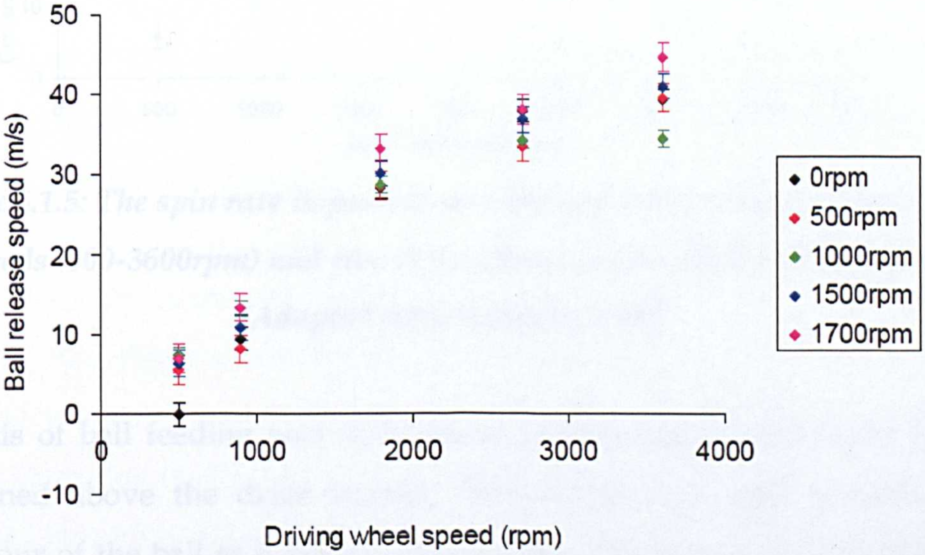


Figure 6.1.4: The ball release speed plotted against driving wheel speed with a range of spin head speeds used (0rpm-1700rpm). (Adapted from Justham, 2007).

Initial tests with spin head speeds of up to 1700 rpm produced deliveries with spin rates of up to 25 rps, this is below the level of an elite spin bowler who could expect to achieve figures of up to 37 rps of rifle spin imparted onto the ball (see Chapter 3). The spin head speed was increased to 3600 rpm, resulting in deliveries with over 50rps imparted onto the ball (see figure 6.1.5). The conclusion from the data achieved during this testing was that there was a linear relationship between the spin head speed and the rate at which the ball spins (Justham, 2007). The ball spin rate data measured from the machine testing using two drive wheel speeds (1800 and 2200 rpm) and seven spin head speeds; 500, 1000, 1500, 2000, 2500, 3000 and 3600 rpm are displayed in figure 6.1.5.

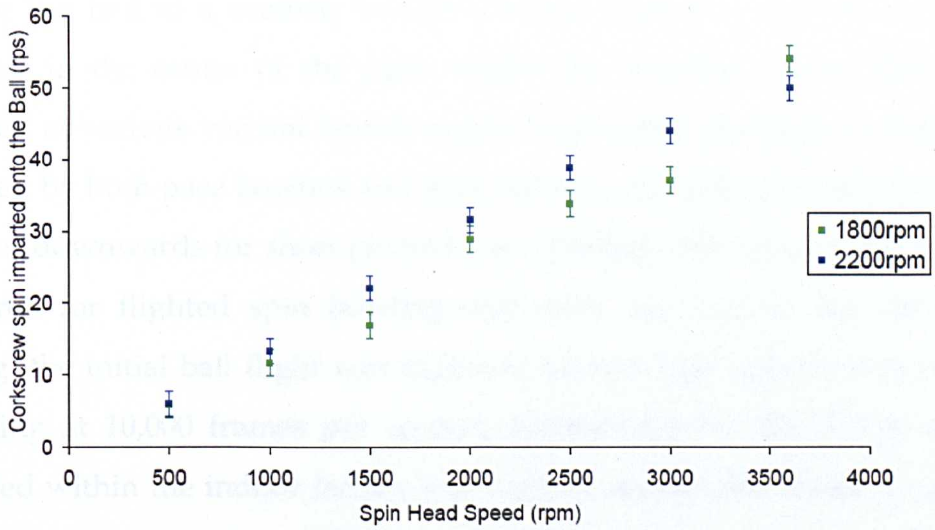


Figure 6.1.5: The spin rate imparted onto the ball using a range of spin head speeds (500-3600rpm) and two drive wheel speeds (1800 and 2200rpm). (Adapted from Justham, 2007)

Analysis of ball feeding was undertaken using a high speed video camera positioned above the drive wheels. The camera was used to record the behaviour of the ball as it passed through the wheels and any movement or alteration in orientation was recorded. The ball was fed into the machine manually which meant the orientation that the ball entered the wheels was controlled. Four orientations were used: upright seam, horizontal seam and two diagonal seams representing inswing and outswing respectively. Additionally the balls were fed into the drive wheels at two distinct "fast" and "slow" speeds where fast input speeds were above 2.25 m/s and slow input speeds were below 0.5 m/s. The results of the testing concluded that the optimum input speed was 2.5 m/s as this speed resulted in minimal alteration of the ball's orientation caused during contact with the wheels (Justham, 2007).

Further testing of the first generation machine was conducted at the ECB National Cricket Centre (NCC) at Loughborough University. The testing carried out was focussed upon the ball flight characteristics at release and the pitching position of each delivery bowled. The machine was positioned to release the ball at a realistic bowler's height (2.45 m - 2.54 m above the ground) in the centre of the pitch within the bowling crease. Balls were released at various vertical launch angles to simulate the types of deliveries released by both pace bowlers and spin bowlers, the angles ranged from 10.4 degrees downwards for short pitched pace bowling deliveries to 13.0 degrees upwards for flighted spin bowling deliveries. As seen in the laboratory testing, the initial ball flight was captured using a high speed video camera sampling at 10,000 frames per second, additionally the Hawk-Eye system installed within the indoor facility was used to capture the trajectory of each delivery output from the machine.

It was concluded from this testing that the performance of the machine in terms of ball flight characteristics (i.e. release speed, spin rate) were in accordance to those seen in the laboratory testing. The additional information gained from this testing was regarding the consistency of pitching position using the HawkEye data. The angle of release appeared to be the determining factor in delivery pitching length. The further below horizontal the launch angle of the delivery, the shorter the ball pitched. Similarly, the higher the launch angle of the delivery, the further down the pitch the ball bounced, although the speed at which the ball was released also influenced this. The greatest variation in the deliveries was seen in the pitching line of the ball. The spread of ball pitching positions horizontally across the pitch was 0.82 metres when the machine was aimed to pitch at the same spot. Justham (2007) attributes this variation to the different levels of corkscrew spin imparted onto the ball by the machine with higher spin rates being imparted onto some deliveries. The greatest variation in pitching position was seen when spin deliveries were bowled where the highest spin rates are witnessed.

6.1.3: First Generation Conclusions:

The series of tests undertaken on the first generation machine indicated that the machine was able to produce deliveries with human realistic ball characteristics imparted. For pace deliveries balls are released at over 96 mph and spin rates are imparted in excess of 50 rps of rifling spin for spin deliveries. These figures suggested that the machine would be able to perform equal to elite level bowlers in terms of pace and spin. The machine however was a laboratory based prototype. There were definite areas of improvement needed if the machine was to progress to support elite training. The entire spin head assembly rotated about the central barrel to create the rifle spin imparting component of the machine. Although this had been a proven method of imparting spin onto the ball the health and safety of the operator and user are compromised by the significant mass (10kg) rotating at high speeds (up to 3600 rpm).

The spin head was engaged manually by moving the blades in to a 66 mm separation using Allen keys. When a ball travelled through the spin-head, the blades were forced to pivot outwards. The force of the ball resulted in the blades being pushed out to their maximum position losing contact with the ball. They then bounce back to their set separation, a result of the tension springs employed to fasten the blades to the barrel when rotating at high speed and subject to centripetal forces. When viewed using a high speed video camera, it was witnessed however that the blades did not return to the barrel within the timeframe of the ball exiting, even at slower input speeds and thus contact time was lost between the spin head and the ball. A next generation machine should exert a controlled force onto the ball for the duration the ball is within the spin head. In addition, if a pace delivery was to be bowled after a spin delivery, the blades would either have to be moved out manually using Allen keys, a time intensive operation, or the ball would travel through the stationary spin head resulting in a loss of speed and potentially a change in orientation due to interaction with the blades.

Throughout the testing of the machine it was observed that the condition of the cricket balls used deteriorated quickly. This was perhaps the consequence of having an efficient mechanism for imparting spin onto the ball and the abrasive interaction between the ball and both the driving wheels and spin head.

Finally for practicality, a next generation machine must be lighter and more compact if it is to be truly portable as desired. Additionally, rather than the current three phase power requirements, a standard British single phase 240 volt plug to enable use in a variety of environments and further improve the safety of the machine for the end user must power the machine.

6.2: Second Generation Machine:

6.2.1: Machine Design:

The second generation spin imparting head was designed to fit onto the existing input wheel assembly from the first generation machine. This meant the performance of the spin head could be evaluated comparatively with the first generation machine (see figure 6.2.1).

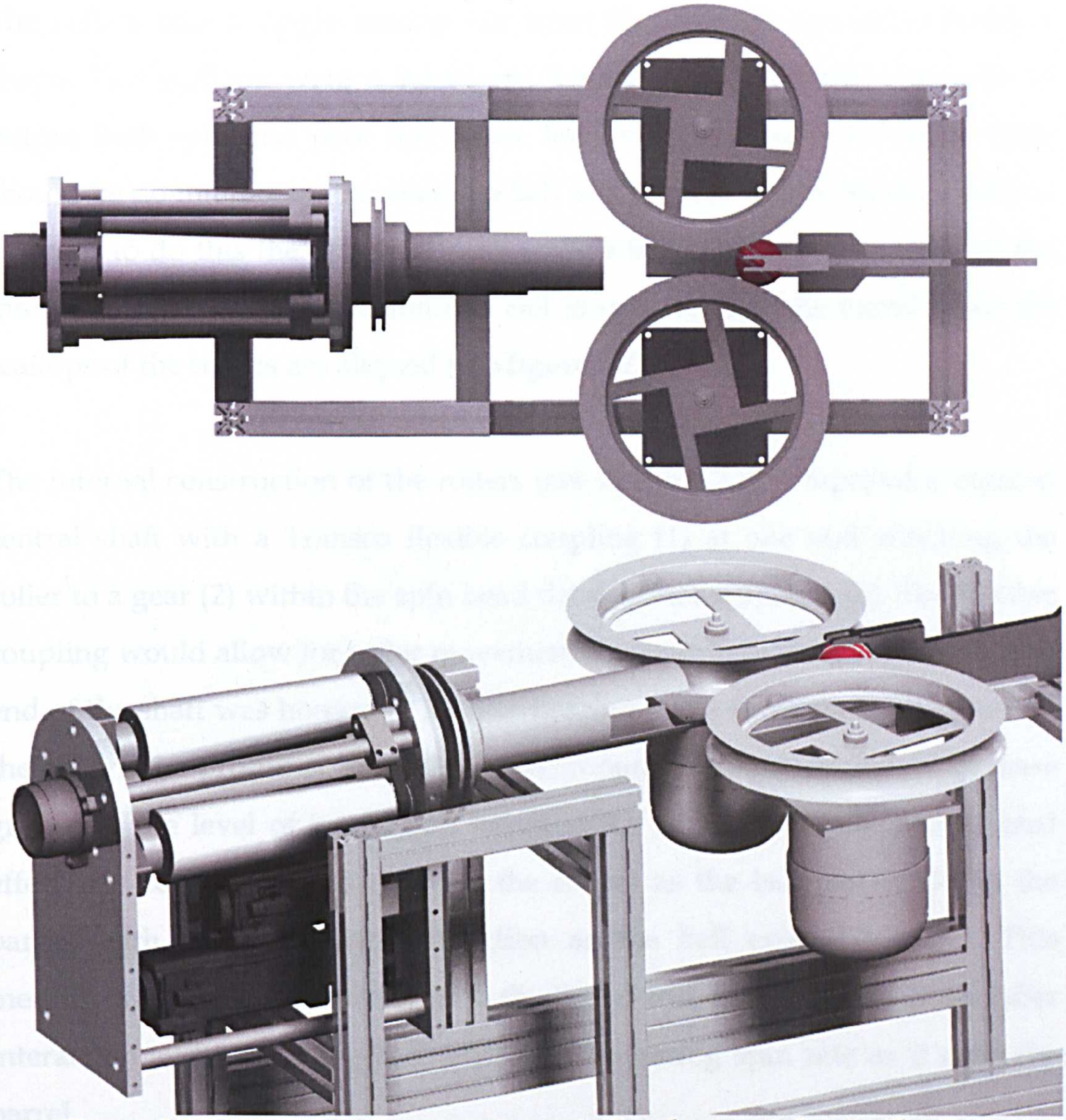


Figure 6.2.1: The second generation spin head mounted onto the first generation machine input mechanism.

The new design had three rotating rollers inset into a central barrel. The rollers were belt driven by a single phase Lenze motor (MCS 09 servo planetary geared motor) controlled using a Lenze 9400 servo drive and housed underneath the central barrel, fixed onto a mounting plate. The outer material used for the rollers was Delrin (Polyoxymethylene), the engineering thermoplastic used in the "lands" of the first generation machine's spin head. This material was chosen as it is durable (impact strength = 1.5 ft-lbs/in), easily machined and it has a low coefficient of friction (dynamic = 0.19) minimising the spin head interaction on the resultant forward speed of the ball.

The rollers had a single scallop cut from the original tapered cylindrical shape. The scallops were a necessary feature if the machine was able to output both spin and pace deliveries. Ideally for the pace deliveries there should be no interaction between the ball and the rifle spin imparting rollers. In order to do this the profile of each scallop had to match the profile of the internal wall of the barrel enabling a ball to pass through the barrel when the scallops of the rollers are aligned (see figure 6.2.7).

The internal construction of the rollers (see figure 6.2.2) comprised a tapered central shaft with a Transco flexible coupling (1) at one end attaching the roller to a gear (2) within the spin head driving motor system (3). The flexible coupling would allow for roller movement during interaction with a ball. The end of the shaft was housed in a roller bearing (4) to allow for the rotation of the roller. The profile of the rollers' Delrin outer (5) was tapered to increase gradually the level of interaction between the rollers and ball. The desired effect was to increase the effect of the rollers as the ball travels down the barrel, with the maximum interaction as the ball exits the barrel. This measure would expectantly reduce the speed lost on the ball due to roller interaction and impart the ball with an accelerating spin rate as it exits the barrel

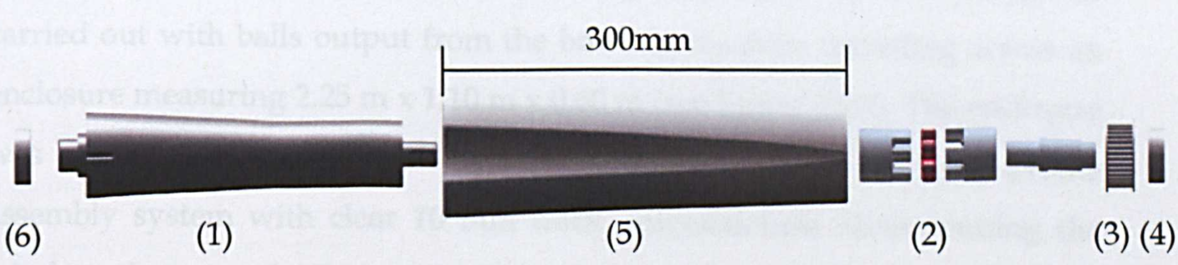


Figure 6.2.2: An exploded view of the internal roller construction.

At the other end of the central shaft was a second roller bearing ((6) Figure 6.2.2), attached to a spring loaded block held within a housing on the end mounting plate (see figure 6.2.3). This housing only allowed the roller to move in one plane away from the barrel upon contact with the ball as there could be no sideways movement. This meant the rollers were able to move longitudinally allowing the ball to pass through the barrel whilst preventing lateral deflection and maintaining the rollers' contact with the ball.

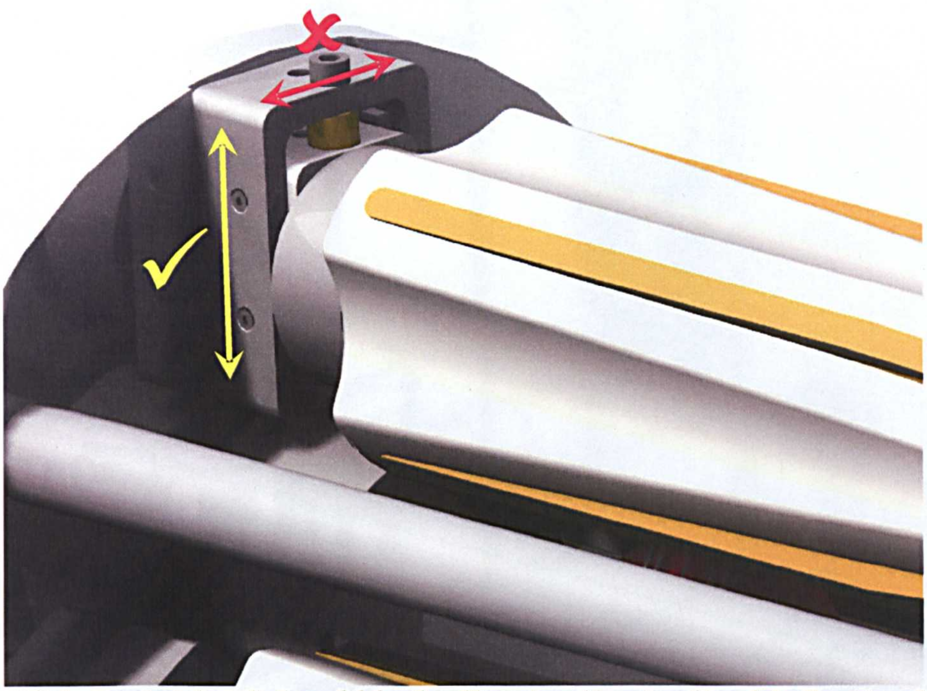


Figure 6.2.3: Spring loaded end block allowing longitudinal deflection but not lateral deflection.

6.2.2: Testing Environment:

The Sports Technology Research Laboratory at Loughborough University was the location chosen for laboratory testing. High-speed camera testing was carried out with balls output from the bowling machine travelling across an enclosure measuring 2.25 m x 1.10 m x 0.60 m (see figure 6.2.4). The enclosure was constructed from 40 mm diameter Rose and Krieger BLOCAN profile assembly system with clear 10 mm thick polycarbonate sheet forming the windows between the Rose and Krieger beams. The enclosure minimised the possibility of the ball rebounding and injuring the investigator or damaging surrounding equipment. Padding was placed within the enclosure to minimise damage to, and cushion the impact between the ball and enclosure.

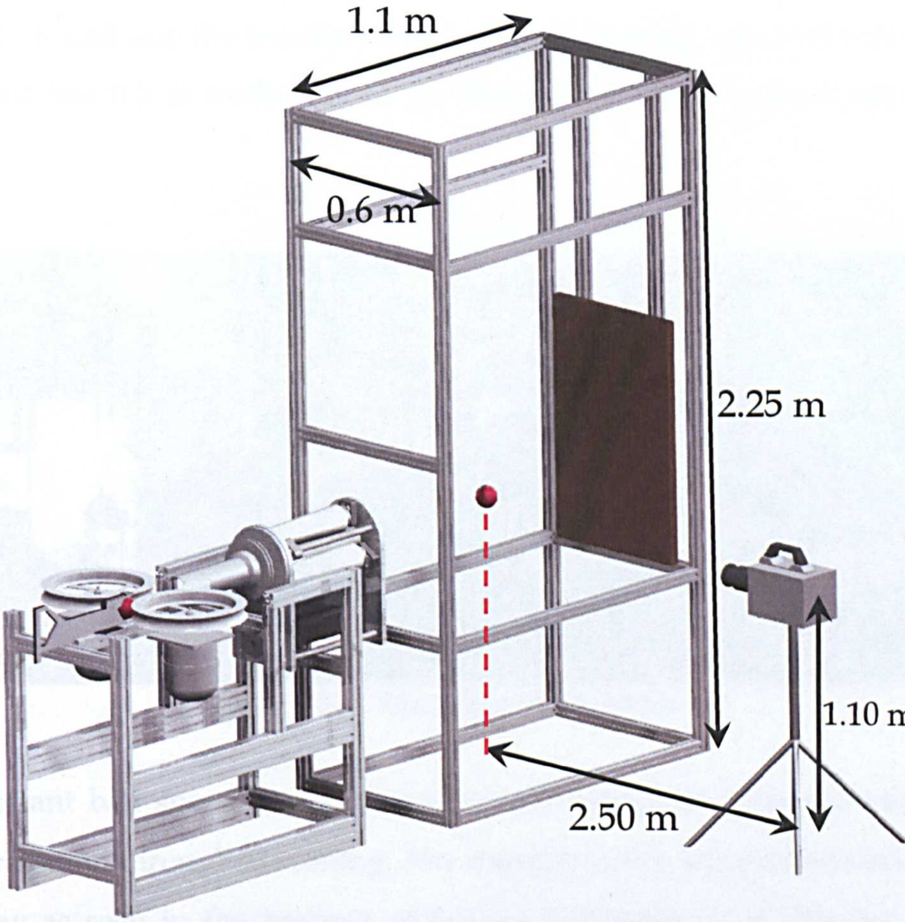


Figure 6.2.4: Laboratory experimental setup.

A Photron Fastcam SA1 high-speed video camera was used to record the ball as it was output from the machine, recording at a rate of 10,000 frames per second. The lens chosen was an AF Zoom-Nikkor f/2.8-4D IF Nikon. The camera was linked to a laptop through a Gigabyte Ethernet cable which was used to download the captured videos for future analysis using Image Pro Analyser software. An identical analysis procedure was used for the spin and speed measurement of output deliveries as seen in Chapter 3 when quantifying cricket bowling (see figure 3.5.1).

The high-speed camera was mounted onto a standard Manfrotto tripod at a height of 1.10 metres from the floor and 2.50 metres from the nominal line of ball flight (see figure 6.2.4). The measurement region was set to 750 mm x 550 mm which corresponded to a 768 x 512 camera pixel resolution at 10,000 frames per second. One ARRI Pocket Par 400 Watt floodlight was used to artificially illuminate the measurement region. The lamp was positioned 0.25 m in front and 0.5 m to the left of the high-speed video camera (see figure 6.2.5)

Figure 5.2.5: The laboratory setup.

The resultant ball speed and the level of spin imparted were the variables concentrated on throughout testing. The measurements were calculated in the same way as seen in the analysis of human performance in Chapter 3 (see figure 3.5.1).

6.2.3: Spin-Head Evolution:

During the course of the research project the spin head has undergone a series of five design alterations. This section will review each of the designs, the spin imparting and resultant speed performance of each and illustrate the changes made.

Spin Head One

The initial design featured a single scallop cut from the Delrin "skin" of the roller (see figure 6.2.6). The radius of the scallop was 38 mm, equal to the internal radius of the central barrel within the machine.

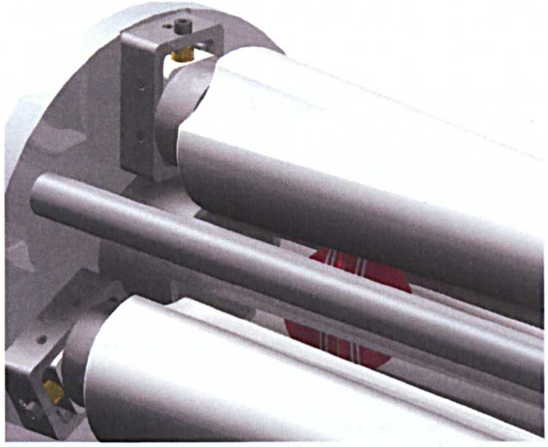


Figure 6.2.6: The single scallop roller design seen in spin head one.

The rollers were positioned within the spin head such that the scallops could be aligned to leave the barrel clear for pace deliveries where rifle spin is not required (see figure 6.2.7 (a)). Using a motor with an encoder would enable the alignment of the scallops for all three rollers.

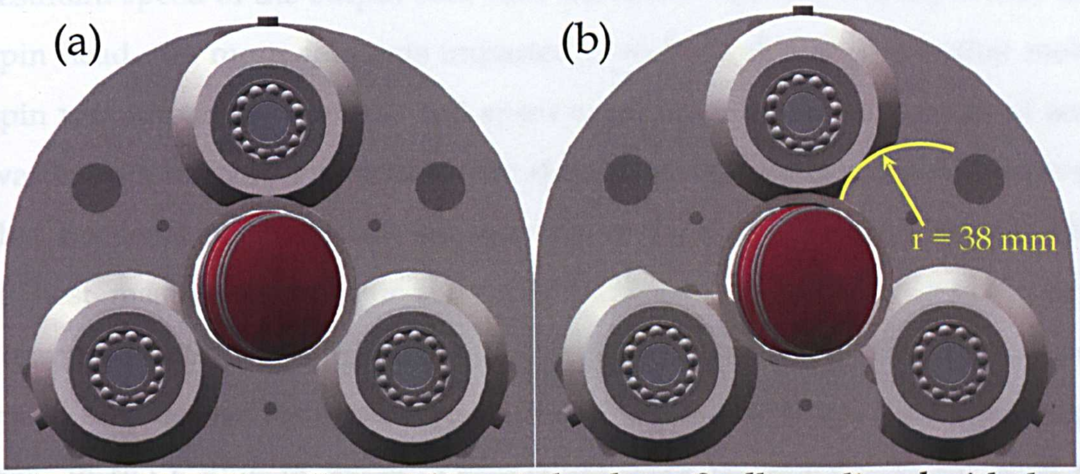


Figure 6.2.7: The rollers within spin head one. Scallops aligned with the central barrel (a) and contacting the ball when rotating (b).

Spin head one was tested within the laboratory setup seen in figure 6.2.4. The data displayed in figure 6.2.8 compares the resultant speed of deliveries with the spin rate imparted. Four different drive wheel speeds (1500, 1800, 2000, 2200 rpm) were compared when the rollers within the spin head were rotating at 3000 rpm. Mean values are plotted (each point representative of 10 deliveries) with error bars representing the standard error in the mean.

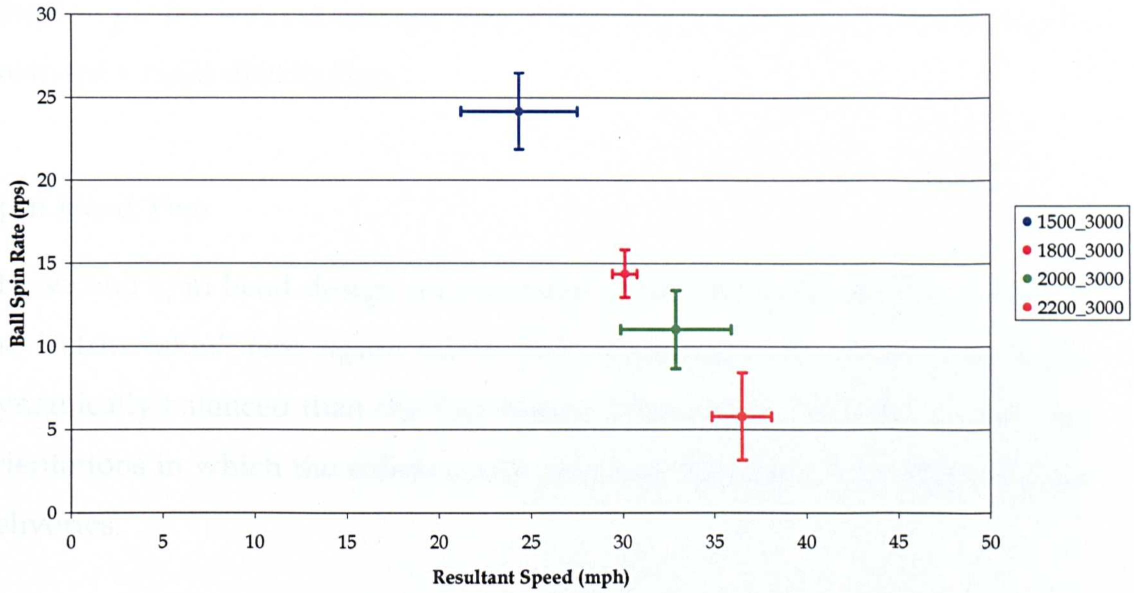


Figure 6.2.8: The spin rate imparted and resultant speed of deliveries output from spin head one.

As perhaps expected, the slower the speed of the drive wheels, the slower the resultant speed of the output ball. Also the slower the ball was input into the spin head, the more spin was imparted onto the ball suggesting that more spin was imparted when the ball spent more time within the spin head and was subject to more interaction with the rollers. It should be noted however that the level of spin imparted was not as high as had been hoped. The highest mean level of spin seen was 24.17 rps (i.e. 48% efficiency when compared with the 50 rps spin head velocity) when 1500 rpm drive wheel speed was used. This is considerably lower than the 50 rps (83% efficiency) seen in the testing of the first generation machine and the 37 rps seen in player testing (see Chapter 3).

During the initial testing it was noted that the rollers were not dynamically balanced when rotating at speeds above 2000 rpm. It was concluded that the cause for the vibrations occurring was the single scallop cut-out as this had moved the centre of mass of the roller away from the centre of geometry. An alteration was made to the profile of the rollers and a second scallop of identical profile was cut out opposite to the original giving each roller a more balanced weight distribution.

Spin Head Two

The second spin head design incorporated rollers with two scallops cut from the Delrin "skin" (see figure 6.2.9). This meant that the rollers were more dynamically balanced than the first design. It also meant that there were two orientations in which the rollers could sit where the barrel was clear for pace deliveries.

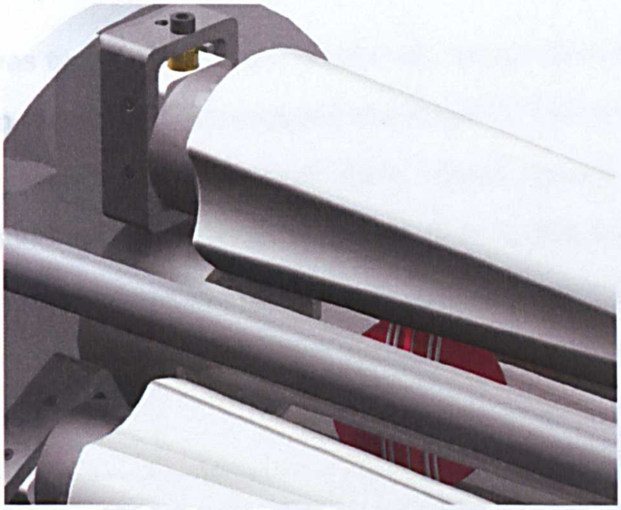


Figure 6.2.9: The dual scallop design seen in spin head two.

The varying orientation of rollers is illustrated in figure 6.2.10 with the rollers aligned with the central barrel (a) and when rotated through 90 degrees (b). The addition of a second scallop reduced the potential contact are between the rollers and ball by a maximum of 15%.

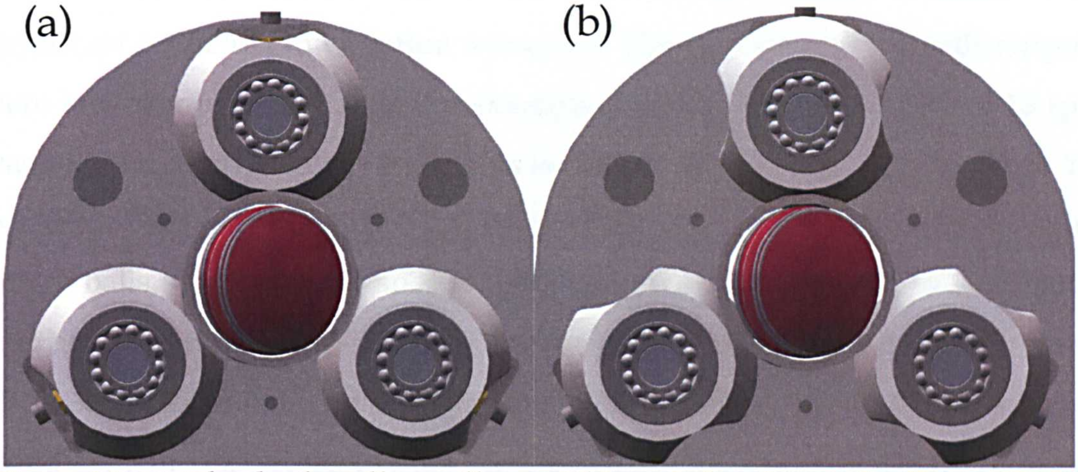


Figure 6.2.10: The dual scallop rollers within spin head two. Scallops aligned with the central barrel (a) and contacting the ball when rotating (b).

Spin head two was tested within the laboratory setup seen in figure 6.2.5. The data displayed in figure 6.2.11 compares the resultant speed of deliveries with the spin rate imparted. The same four drive wheel speeds (1500, 1800, 2000, 2200 rpm) and 3000 rpm spin head speed as seen in the testing of spin head one were used. Mean values are plotted (each point representing 10 deliveries) with error bars representing the standard error in the mean.

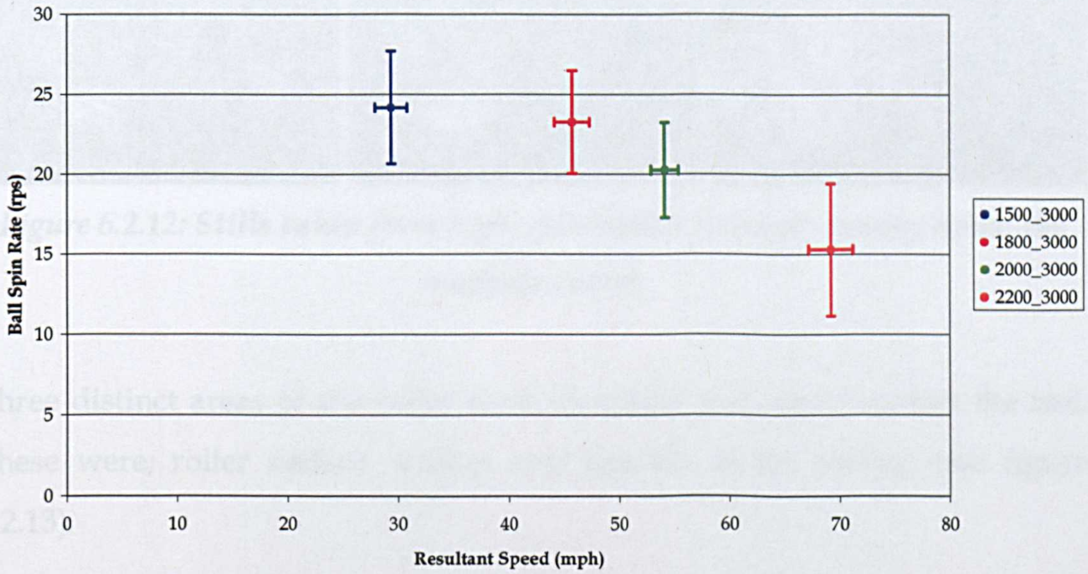


Figure 6.2.11: The spin rate imparted and resultant speed of deliveries output from spin head two.

The even distribution of mass in the second roller design resulted in a significant reduction in vibration witnessed. The spin rates of the balls output were however unpredictable. For example, a difference in spin rate of 15 rps was seen for alternate deliveries. This is further demonstrated by the large Y-axis error bars seen in figure 6.2.11 (mean ± 4.0 rps). It is notable that the spin rate of balls input at faster speeds had increased in comparison to spin head one, however the highest mean spin rate seen had not significantly improved (24.18 Vs. 24.17 rps). To investigate the variation in spin rate imparted, a high-speed camera was set up to view directly down the barrel of the machine as balls passed through the spin head. This camera recorded the interaction between the ball and the rollers (see figure 6.2.12). The drive wheel speed was set to 2000 rpm with a spin head speed of 3000 rpm. The hypothesis of this testing was that the spin rate imparted onto the ball was affected by the part of the roller that made contact with the ball.

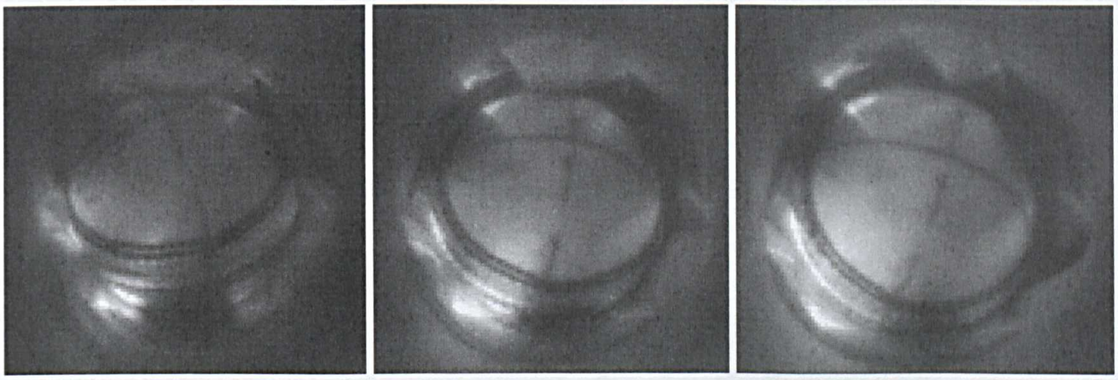


Figure 6.2.12: Stills taken from high-speed video footage viewing down the machine barrel.

Three distinct areas of the roller were identified that could contact the ball. These were; roller surface, scallop and knuckle of the scallop (see figure 6.2.13).

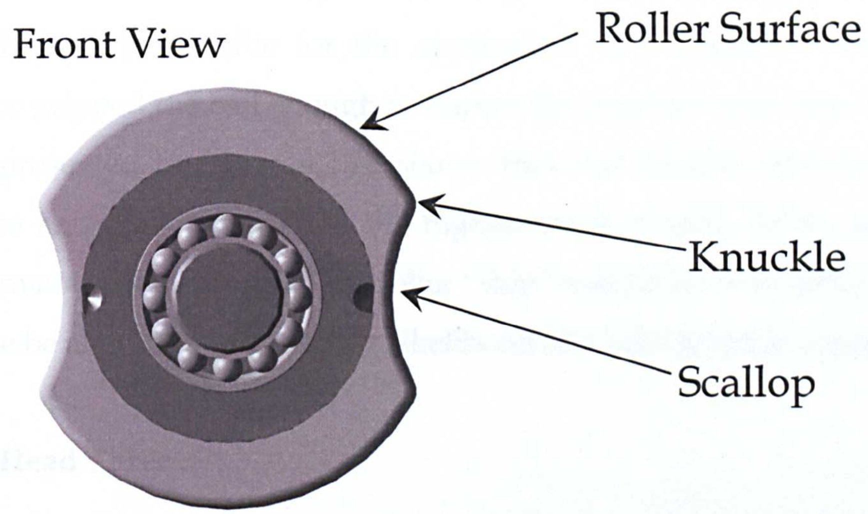


Figure 6.2.13: Front view of roller two with three areas of contact.

The results of this investigation showed that there was a greater amount of spin imparted onto the ball when interaction occurred between the ball and the knuckle of a scallop rather than the surface of the roller or a scallop (see figure 6.2.14). These data are summarised in figure 6.2.14 where mean spin rate values are displayed for each of the contact positions with error bars representing standard error in the mean.

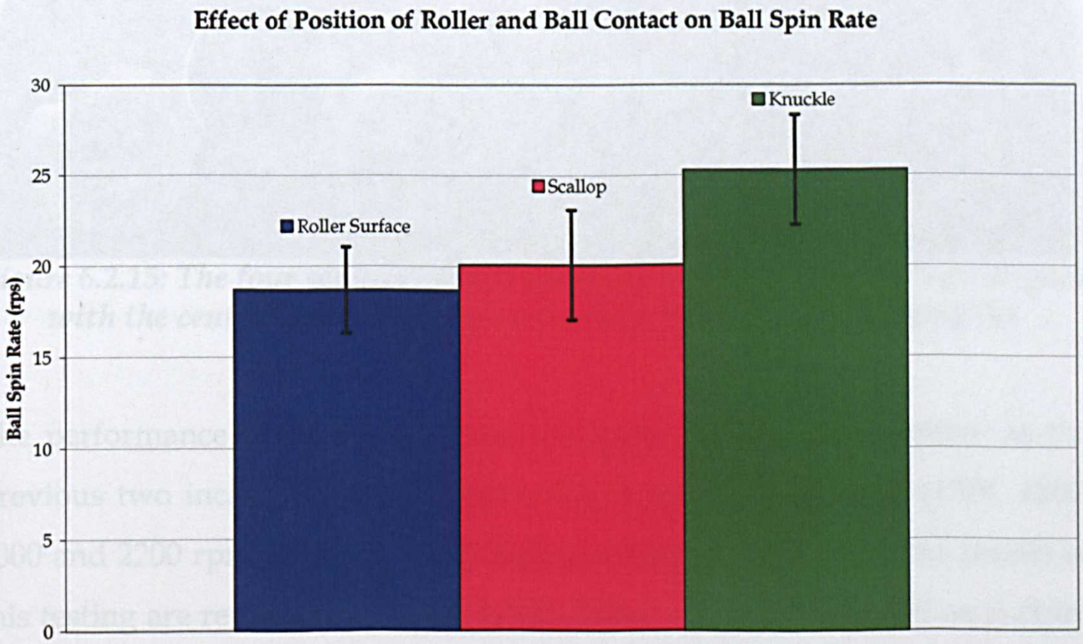


Figure 6.2.14: The effect of roller/ball contact position on spin rate imparted.

The results of this case study called into question the suitability of a primarily cylindrical roller profile for the application and whether a smooth roller surface gripped the ball enough to impart the required spin onto the ball. The data presented in figure 6.2.14 shows that the knuckle between the roller surface and scallop imparted the highest level of spin. Before any changes were made to the surface of the roller "skin" material it was preferred that the profile be altered to improve the likelihood of a ball/knuckle contact.

Spin Head Three

The third generation of spin head incorporated rollers with four scallops (see figure 6.2.15), doubling the likelihood of contact between ball and roller knuckle. The hypothesis was that by increasing the chance of contacting the ball with the roller knuckle, the spin rate imparted would increase.

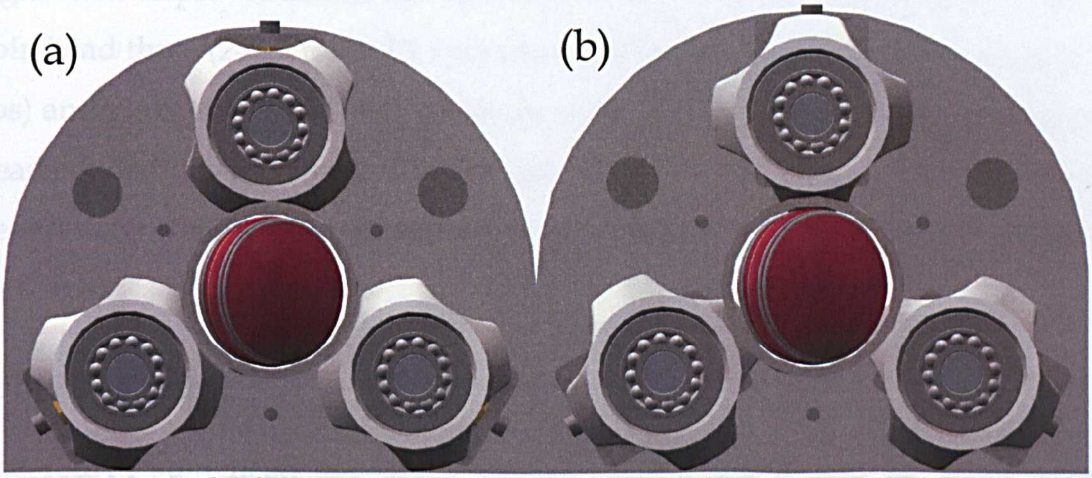


Figure 6.2.15: The four scallop rollers within spin head three. Scallops aligned with the central barrel (a) and contacting the ball when rotating (b).

The performance of spin head three was tested in the same manner as the previous two incarnations. Four drive wheel speeds were used (1500, 1800, 2000 and 2200 rpm) with the spin head operating at 3000 rpm. The results of this testing are reviewed in figure 6.2.16. Mean values are plotted, each point represents 10 deliveries with error bars representing the standard error in the mean.

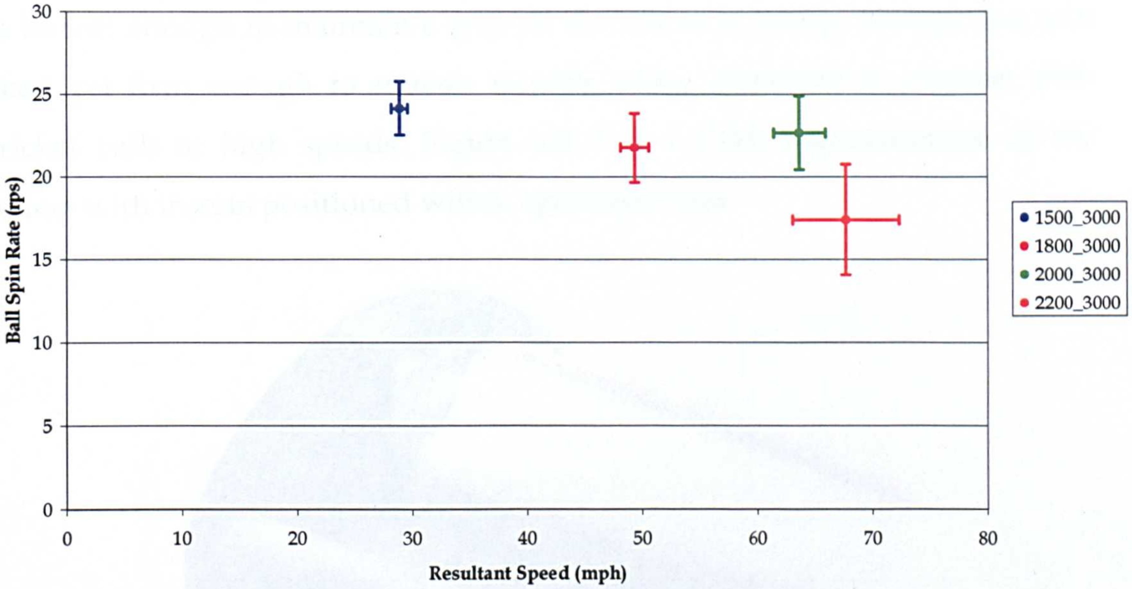


Figure 6.2.16: The spin rate imparted and resultant speed of deliveries output from spin head three.

The results of testing displayed in figure 6.2.16 indicate that there was no significant improvement in ball spin rate seen for the deliveries output from spin head three (24.23 rps ± 2.1 rps) when compared to spin head's one (24.17 rps) and two (24.18 rps). The maximum mean spin rate seen for all three spin heads failed to go above 25 rps, still significantly lower than the first generation machine (50 rps) and the human performance analysed in Chapter 3 (37 rps).

Spin Head Four

The fourth spin head saw the most radical change of any of the design phases. The second generation spin head's rotating roller design, while being safer than the first generation rotating barrel was not as efficient at imparting spin. Four dovetail slots were cut along the length of the rollers down the middle of the roller surface. These slots were the same width as the lands seen within the rotating barrel of the first generation machine (8.70 mm). Placed into these slots were polyurethane (Techsil F70 flexible casting polyurethane) inserts. These inserts had a shore hardness of 70 on the ASTM D2240 Type A scale (National Physics Laboratory, 2008) The material was felt to be soft enough to maintain a grip on the ball as it passes through the spin head yet firm enough to remain durable when subjected to impacts with cricket balls at high speeds. Figure 6.2.17 is a CAD representation of the rollers with inserts positioned within spin head four.

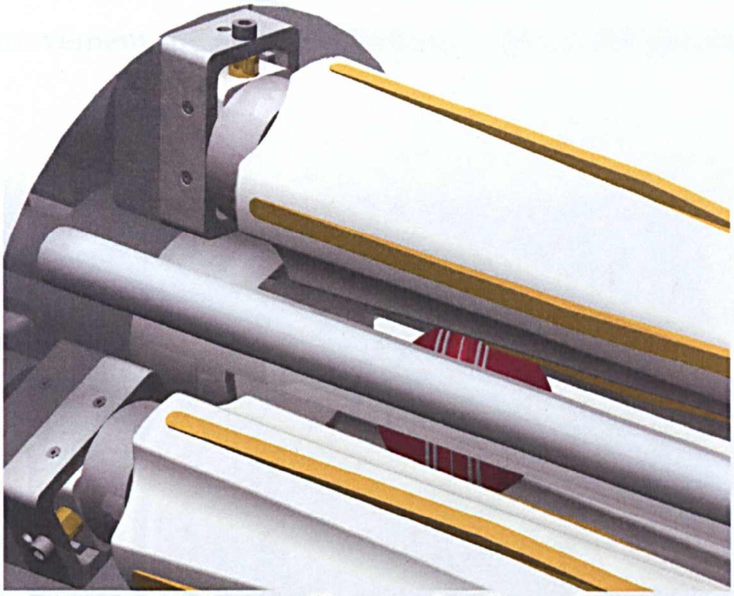


Figure 6.2.17: Rollers with four scallops and polyurethane inserts slotted into the roller profile.

The polyurethane inserts were profiled such that they were parallel for 175 mm of their length (see figure 6.2.18) with a shorter 5 degree taper (100 mm) to allow the ball to enter the spin head before contact was made and spin imparted.

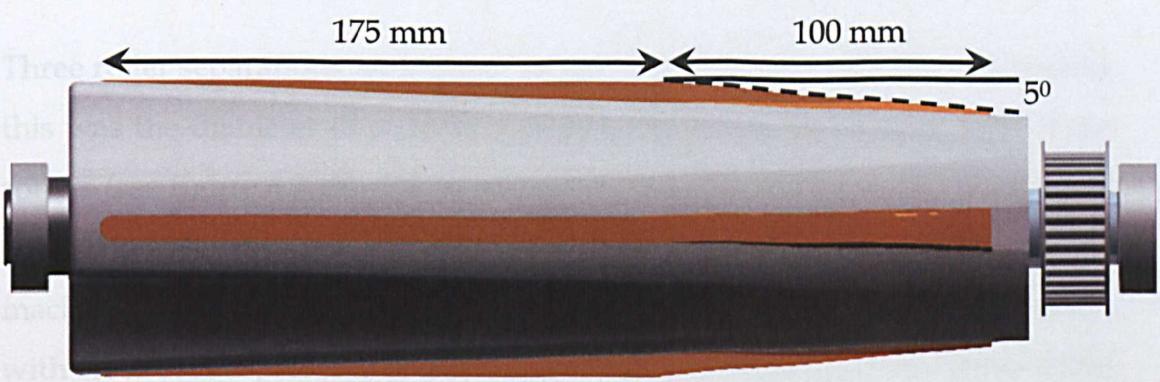


Figure 6.2.18: The roller design with polyurethane inserts profiled to produce a parallel surface for 175 mm of the roller and 100 mm with a 5 degree taper.

Testing was conducted to examine the effect of roller separation, the distance between the rollers that the ball would travel through (see figure 6.2.19). The separation was controlled using screws within the roller housing (see Figure 6.2.3) defining the minimum roller separation while a compression spring (60 N/m) in the opposite end of the housing regulated the amount of longitudinal movement the roller underwent when a ball passed through the spin head.

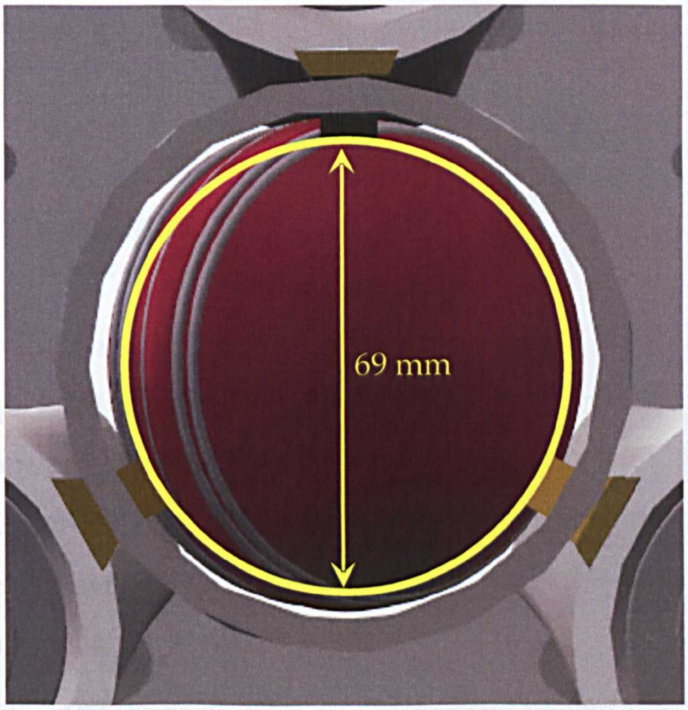


Figure 6.2.19: The measurement of roller separation within the spin head.

Three roller separations were used (i.e. 68, 69 and 70 mm effective diameters), this was the diameter of a circle positioned to touch the apex of each of the rollers (see figure 6.2.19). The results of testing are displayed in figure 6.2.20 comparing the resultant speed and ball spin rate of balls output from the machine. Mean figures are plotted (each point representing five deliveries) with error bars representing the standard error in the mean. Four drive wheel speeds were compared, these can be differentiated by colour while roller separation is denoted by the thickness of error bars (see legend, figure 6.2.20).

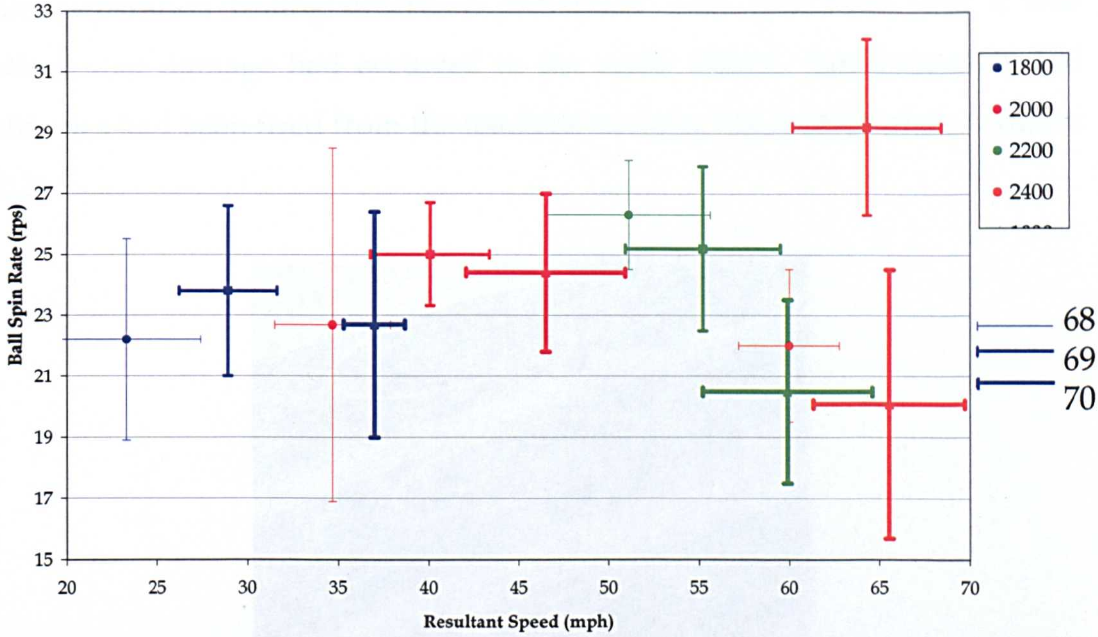


Figure 6.2.20: The resultant speeds and spin rates of output deliveries using three roller separations; 68, 69 and 70mm.

At 1800 drive wheel speed there is no significant increase in spin imparted (68mm - 22.2 rps ± 3.3, 69mm - 23.8 rps ± 2.8, 70mm - 22.7 rps ± 3.7) although the resultant forward speed increases at larger separation (23.3mph at 68mm - 37.0mph at 70mm). Similar spin performance characteristics are observed at 2000 drive wheel speed (68mm - 22.7 rps ± 5.8, 69mm - 25.0 rps ± 1.7, 70mm - 24.4 rps ± 2.6) whilst at 2200 although an increase in forward velocity is observed there is a decrease in the amount of spin imparted as the separation is increased (68mm - 26.3 rps ± 1.8, 69mm - 25.2 rps ± 2.7, 70mm - 20.5 rps ± 3.0). The behaviour at the highest drive wheel speeds is more complex however, as spin is occasionally imparted onto the ball prior to entering the spinhead. This can result in misleadingly high spin results. The 69 mm roller separation produced the most linear results in terms of spin rate imparted. This was the final separation chosen for the machine as it was deemed the most consistent (standard error values of ± 2.8, 1.7, 2.7 and 2.9 rps for 1800, 2000, 2200 and 2400 rpm drive wheel speeds respectively).

After each testing session the machine was serviced to ensure that each of the components was in optimum condition. After initial machine testing and the roller separation testing described previously with spin head four it was noticed that damage had occurred to the roller inserts. Approximately 100 deliveries had been fired from the machine to cause the damage seen in figure 6.2.21.

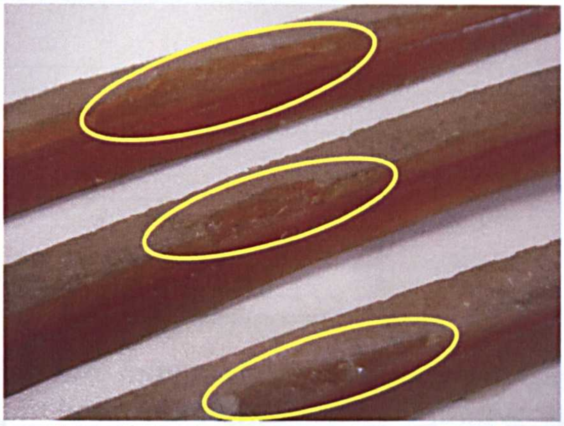


Figure 6.2.21: Examples of damage occurring to 70 shore hardness inserts.

Although not achieving the performance of first prototype the spin imparting capability of the rollers with inserts had been encouraging with peak spin rates measured of over 30 rps. Due to the damage incurred by the 70 shore hardness inserts it was decided that a more resistive material should be trialled. A 95 shore hardness (ASTM D2240 Type A scale) casting polyurethane elastomer was chosen (Axson UR 3558). This product was chosen due to the manufacturer's claims of it being extremely impact resistant (abrasion resistance of 80 mg/100U, tensile strength of 19 MPa), having good tear strength (57 kN/m) and a working temperature of -40 to 80^{o} C

Spin head four with 95 shore hardness inserts was tested in the same manner as the three previous spin head designs, using four drive wheel speeds and a constant spin head speed of 3000 rpm. Spin head separation was set at 69mm. The drive wheel speeds used were 1800, 2000, 2200, 2400 rpm. The results of testing are displayed in figure 6.2.22. Mean values are plotted (each point representing 10 deliveries) with error bars representing the standard error in the mean.

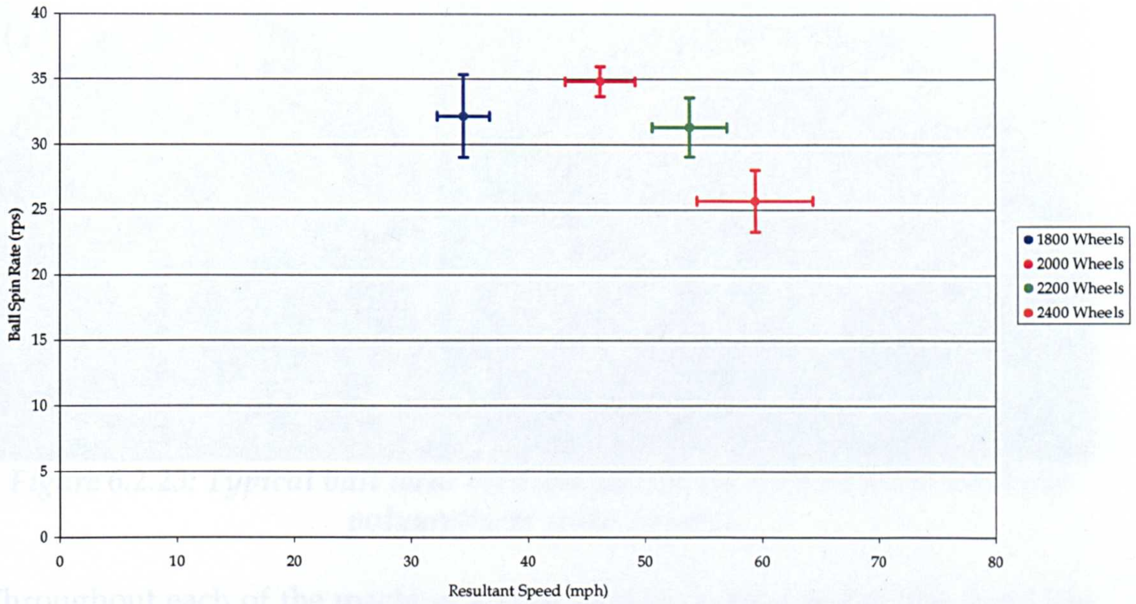


Figure 6.2.22: The spin rate imparted and resultant speed of deliveries output from spin head four with 95 shore hardness inserts.

The spin imparting performance of spin head four with 95 shore hardness inserts was the best seen to that point. It was also the most consistent in terms of ball speed and spin rate, confirmed by the smaller error bars (speed, mean ± 3mph, spin mean ± 2 rps) seen in figure 6.2.22. When 2000 rpm drive wheels were used a mean spin rate of ≈ 35 rps was witnessed, the consistency in this spin rate was also notable, with a standard error in the mean value of ±1.15 rps.

During testing it was noted that the cricket balls used appeared to be wearing more quickly than during previous tests. Figure 6.2.23 is a composite of two photographs of one of the balls. In the images it can be seen that the seam of the ball has been torn (1) and the leather surface has been cut (2). Overall the condition of the ball deteriorated more than would be seen under match conditions where it is common that bowlers' hands will become sore if bowling for prolonged periods, this is especially the case for spin bowlers. In this case, however the ball was significantly softer than the material it was coming into contact with (i.e. the 95 shore hardness inserts) and was thus becoming worn when put through the spin head.

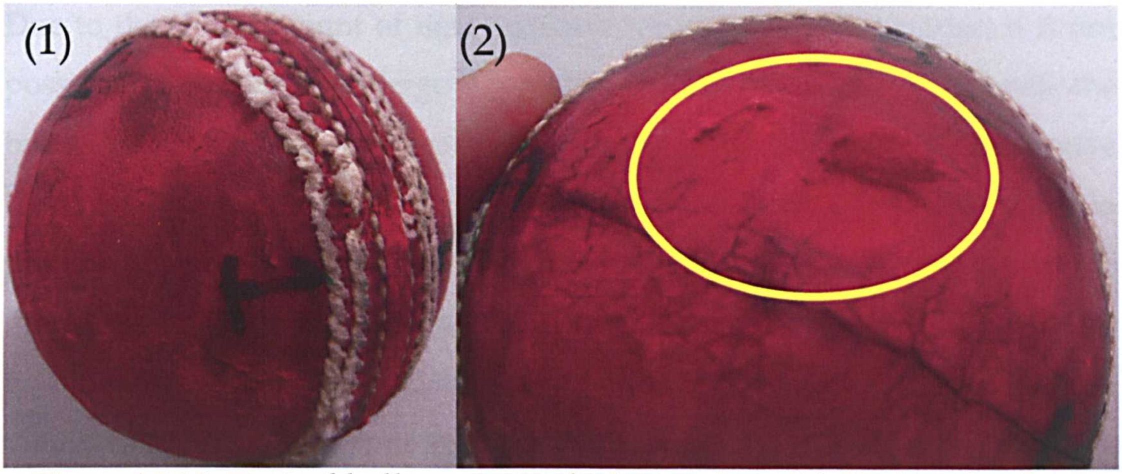


Figure 6.2.23: Typical ball wear seen during testing with 90 shore hardness polyurethane roller inserts.

Throughout each of the machine testing sessions reviewed the spin head has been set to rotate at 3000 rpm. At this speed the rollers make one complete revolution every 0.02 seconds. Depending on the delivery type selected the ball will enter the spin head at varying speeds from 40 mph up to 100 mph. The faster speed the ball enters the spin head, the shorter time it will spend in the spin head and hence the shorter time it has to make contact with the rollers. An investigation has been carried out to measure the effect the ball speed has on the level of contact available between the ball and rollers. The contact data calculated for a spin head speed of 3000 rpm at a range of input ball speeds (40 – 100 mph) is presented in Table 6.2.1.

Ball Input Speed (mph)	Duration in Barrel (secs)	% of Roller Revolution Completed (3000 rpm)
100	0.0067	33.8
90	0.0075	37.5
80	0.0084	42.0
70	0.0096	48.0
60	0.0112	56.0
50	0.0134	67.2
40	0.0168	84.0

Table 6.2.1: The typical duration a ball spends within the barrel when input at a range of speeds and the percentage of one complete revolution each roller would undergo in that time when rotating at 3000 rpm.

Due to the short amount of time available for ball and roller contact it is not possible for a roller to undergo a complete revolution (at 3000 rpm) while the ball is present in the spin head, even at low input speeds. It is imperative therefore that the ball receives the maximum interaction with the rollers as possible during this short time. This will depend on the initial orientation of the rollers as the ball enters the spin head. Figure 6.2.24 is an illustration of two possible roller orientations with the level of clockwise rotation each would undergo at 3000 rpm annotated for a range of ball input speeds (40 - 100 mph).

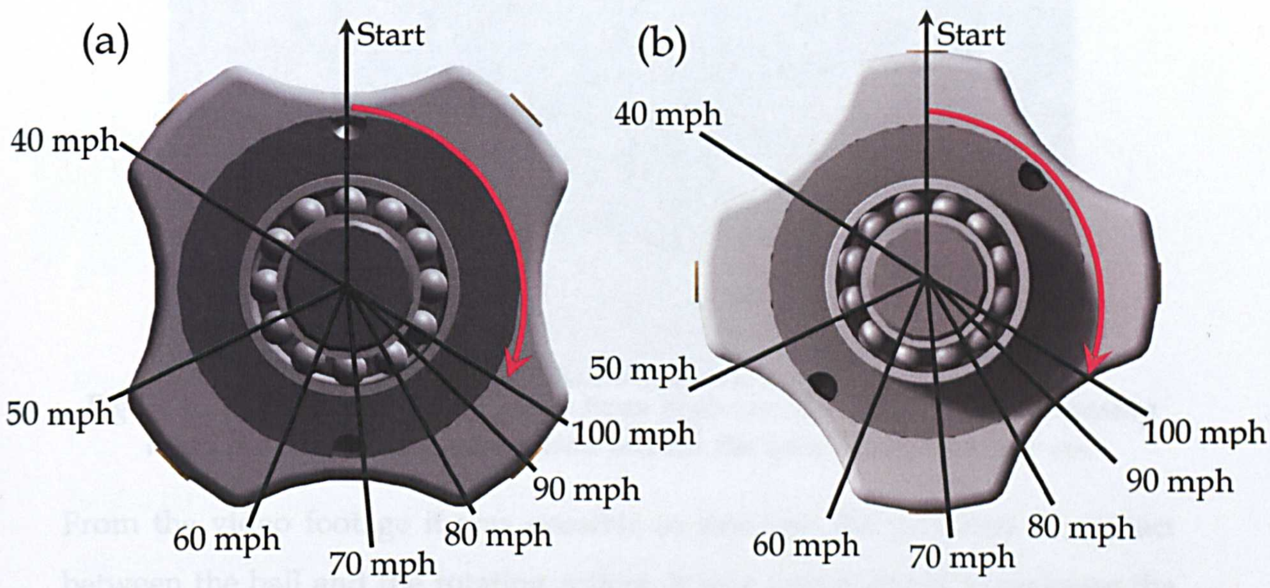


Figure 6.2.24: The level of rotation a roller rotating at 3000 rpm would undergo for the duration a ball spends within the spin head when input at varying speeds (40 mph - 90 mph).

The two orientations seen in figure 6.2.24 are only 45 degrees different, however the level of interaction between roller and ball would be affected. For example, a ball input at 60 mph could receive two points of contact for the duration it was present within the spin head if the roller were initially in position (a), however it would receive three points of contact if the roller were in position (b) as the ball entered the spin head.

Testing was conducted to analyse the behaviour of the ball as it passes through the spin head. A high-speed camera (Photron SA-1) was set up perpendicular to the spin head, positioned such that the ball could be viewed for the duration it spent travelling through the spin head. The high-speed camera was set to record at 10,000 frames per second with two ARRI pocket par 400 HMI lights focussed upon the area of interest providing necessary additional lighting. Figure 6.2.25 is a still image taken from the high-speed video footage.

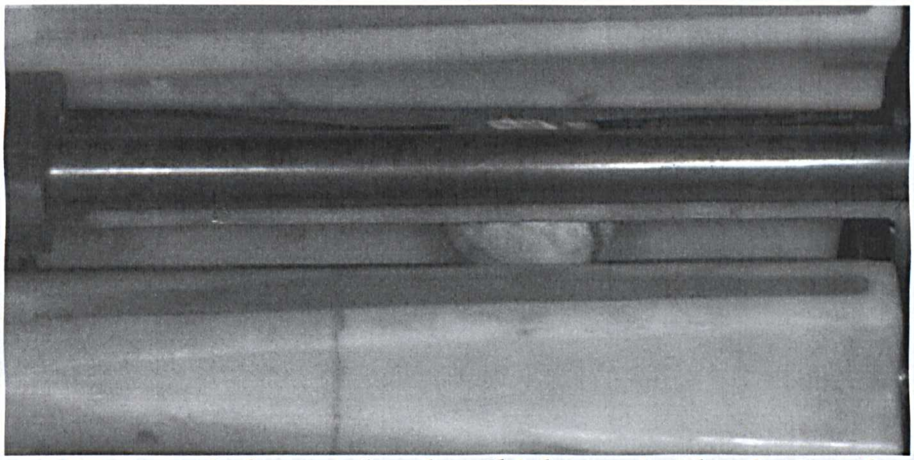


Figure 6.2.25: A single frame taken from high-speed video footage focussing upon ball and roller interaction within the spin head from side on.

From the video footage it was possible to measure the positions of contact between the ball and the rotating rollers. It was also possible to measure the level of rotation the ball underwent during its time in the spin head. The data measured from this testing is displayed graphically in figure 6.2.26. The data shows the point of contact between the ball and the rollers (X axis) and the spin rate imparted onto the ball (Y axis), this was calculated by measuring the level of rotation the ball underwent divided by the time it had taken to rotate. Mean values are plotted representing five deliveries each with four drive wheel speeds used (1800, 2000, 2200, 2400 rpm) with the spin head rollers rotating at 3000 rpm.

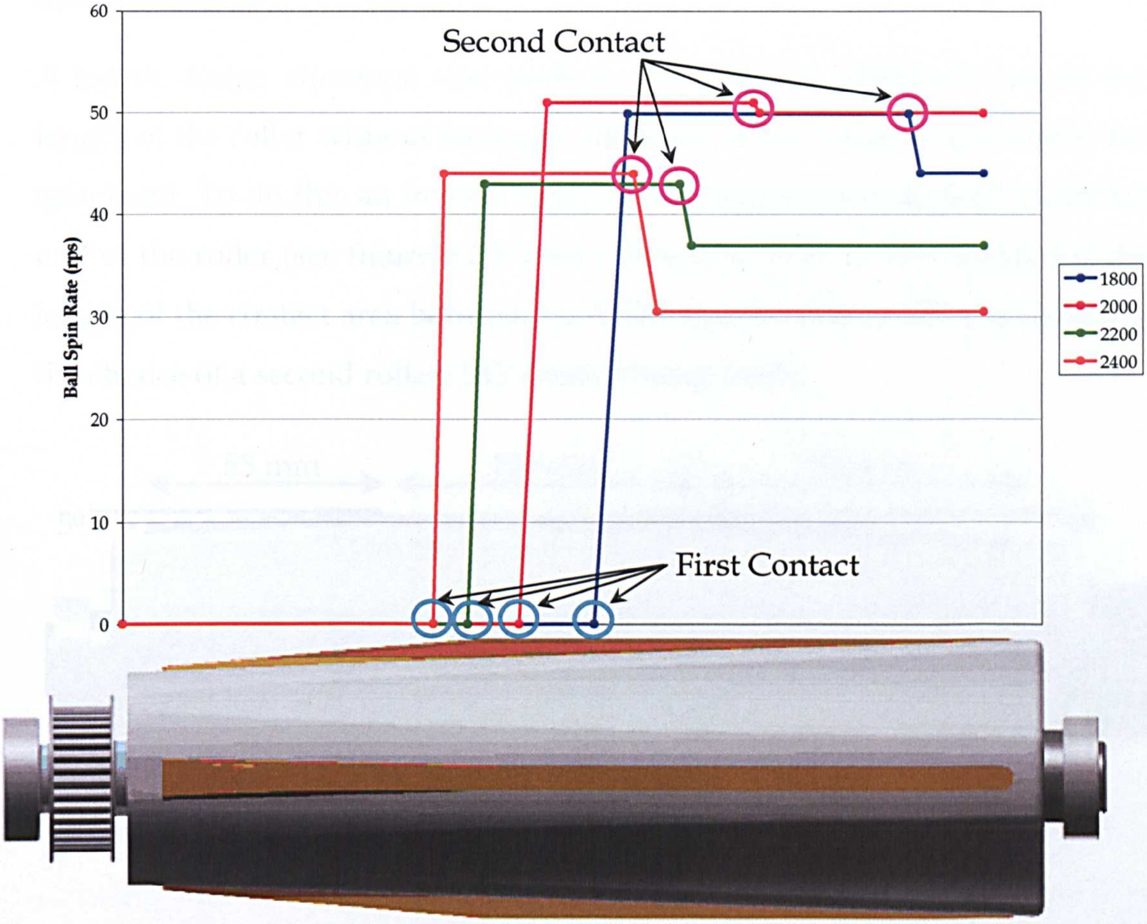


Figure 6.2.26: The position of contact between ball and roller and the effect on ball spin rate.

In the current design, balls typically experience two points of contact with the rollers when travelling through the spin head. The data displayed in figure 6.2.3.21 confirms this, the first point of contact imparting spin onto the ball and the second point of contact reducing the spin rate of the ball to varying degrees (Minimum -2.8 rps, Maximum -13.1 rps). It should be noted that the data displayed in figure 6.2.26 is mean data and therefore the ball spin rate was not reduced every time the ball contacted the rollers for a second time, however, on average this was the case. This was clearly not the desired effect and may have explained the inconsistency in ball spin rates seen during the previous spin head designs as some balls may have only encountered one contact with the rollers resulting in a higher spin rate imparted than those that were subjected to two contacts.

Spin Head Five

A fourth design alteration was made to the rollers to effectively reduce the length of the roller without having to alter any of the components within the spin head. To do this an inverse taper of five degrees was applied to the far end of the roller (see figure 6.2.27) for a length of 55 mm. This shortened the length of the contact area between the roller and the ball to 120 mm reducing the chance of a second roller/ball contact being made.

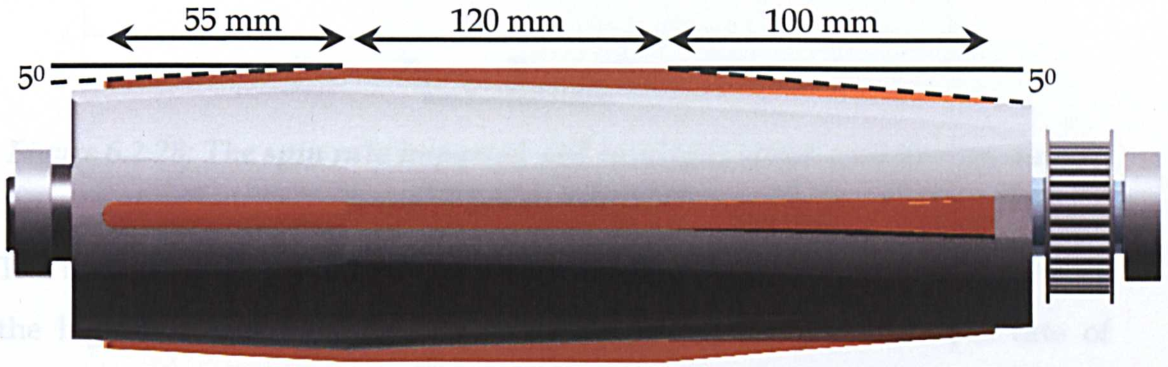


Figure 6.2.27: The roller profile seen in spin head five.

Spin head five was tested in the same manner as the four previous designs, with the rollers rotating at 3000 rpm and four drive wheel speeds used. High-speed video footage was captured as the ball was output from the machine into the safety enclosure. The data measured from this testing is presented in figure 6.2.28 where the ball resultant speed and spin rate are compared. Mean values are plotted (each point representing ten deliveries) with error bars representing the standard error in the mean.

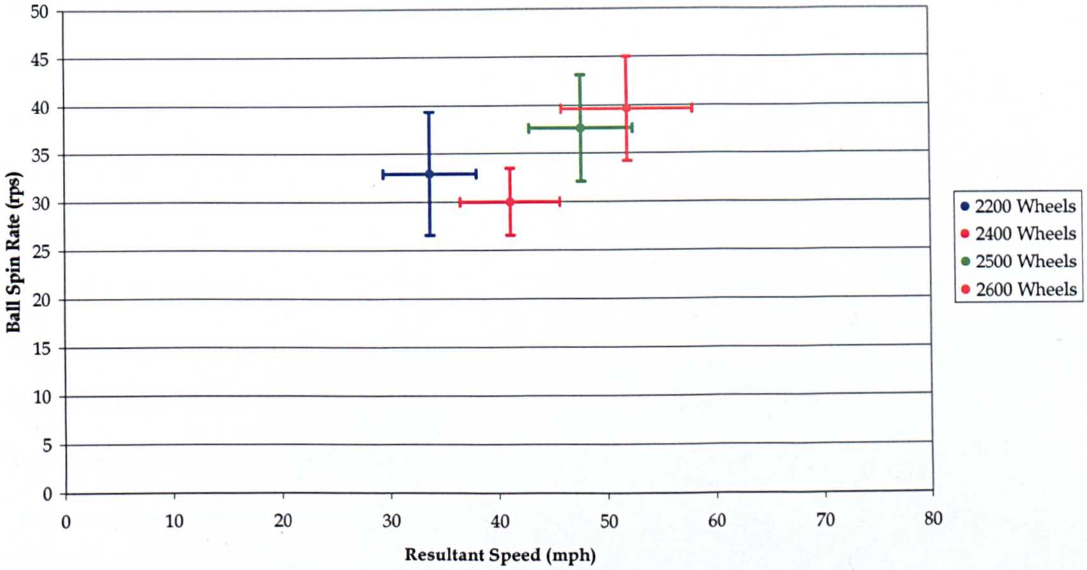


Figure 6.2.28: The spin rate imparted and resultant speed of deliveries output from spin head five.

The ball spin rates measured for deliveries output from spin head five were the highest seen from any of the spin head designs. A peak spin rate of 54.9 rps was measured with the peak mean spin rate of 39.6 rps (79.2% efficiency) for 2600 rpm drive wheels. It is interesting to note that a general trend was that the spin rate of the ball increased as the drive wheel speed increased (gradient of line of best fit = 0.83, see figure 6.2.28). This is in contrast to each of the previous spin head designs where the spin rate imparted has reduced as the speed of the ball has increased.

A further test was conducted to measure the effect of spin head speed on ball spin rate. In order to do this, the drive wheel speed was fixed at 2200 rpm and the speed of the spin head was varied. Four spin head speeds were compared (0 rpm, 1000 rpm, 2000 rpm, and 3000 rpm) and the results are plotted in Figure 6.2.29. Mean results are plotted (each point representing 5 trials) with error bars representing the standard error in the mean values.

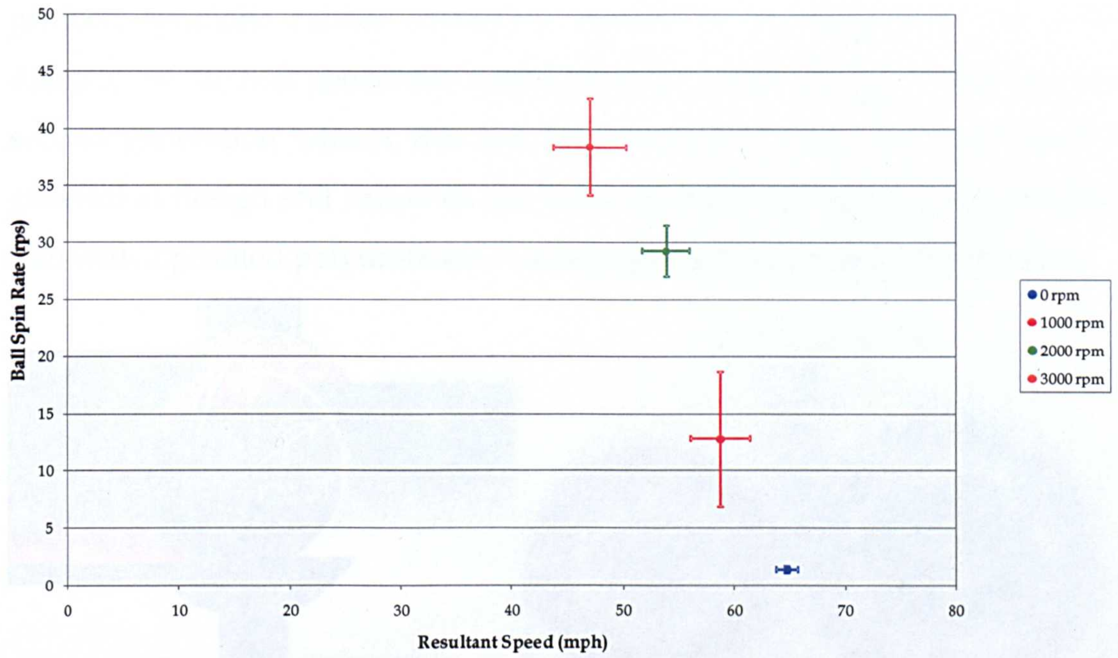


Figure 6.2.29: The effect of altering spin head speed on spin imparting performance: fixed drive wheel speed (2200 rpm) and four spin head speeds.

The data presented in figure 6.2.29 represents an approximately linear shape. As the spin head speed is increased, the ball speed decreases. The peak mean spin rate measured (38.3 rps) is higher than elite performance measured in Chapter 3 (37 rps) and occurred when 3000 rpm spin head speed was used.

6.3: Drive Wheel Design:

One of the areas of improvement identified from the evaluation of the first generation prototype machine was to make the machine more compact, reduce the amount of material "pickup" on the surface of the drive wheels and increase the speed of deliveries if possible. In order to achieve this the components had to become smaller and lighter, an alternative material investigated and contact area between the wheel and the ball increased. The second generation design of the drive wheels will be focussed upon in this section.

The first generation machine wheels were based upon the counter rotating wheels seen in existing cricket bowling machines such as BOLA, where a profiled synthetic rubber coating is applied to a central steel hub. The diameter of the first generation wheels was 350 mm (see figure 6.3.1), for the second generation wheels this has been reduced to 250 mm. The second generation design still followed the same principle of having a steel central hub with a profiled polyurethane coating applied around the circumference.

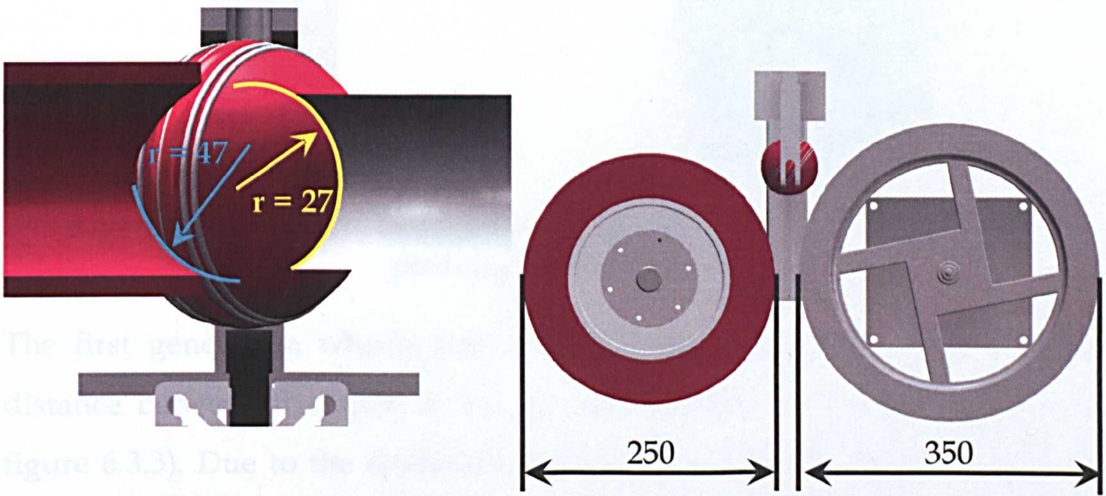


Figure 6.3.1: The curvature of the second generation wheels vs. the first generation (left) and the diameters of the two wheel designs (right).

Due to the smaller diameter of the second generation wheels it was important that the transfer of energy from the wheels to the ball was as efficient as possible due to lower rotational velocity. In order to achieve this, the profile of the polyurethane coating was altered from the profile seen in the first generation wheels. The coating was thicker than seen previously, 60 mm high vs. 45 mm seen in the first generation (see figure 6.3.2). The concave profile also changed from a 27 mm radius seen in the first generation wheels to two halves, top and bottom each with a 47 mm radius (see figure 6.3.1). The final change was to incorporate smaller, single phase motors to power the wheels. Lenze MCS 09 servo planetary geared motors were sourced controlled using Lenze 9400 servo drives (see figure 6.3.2).

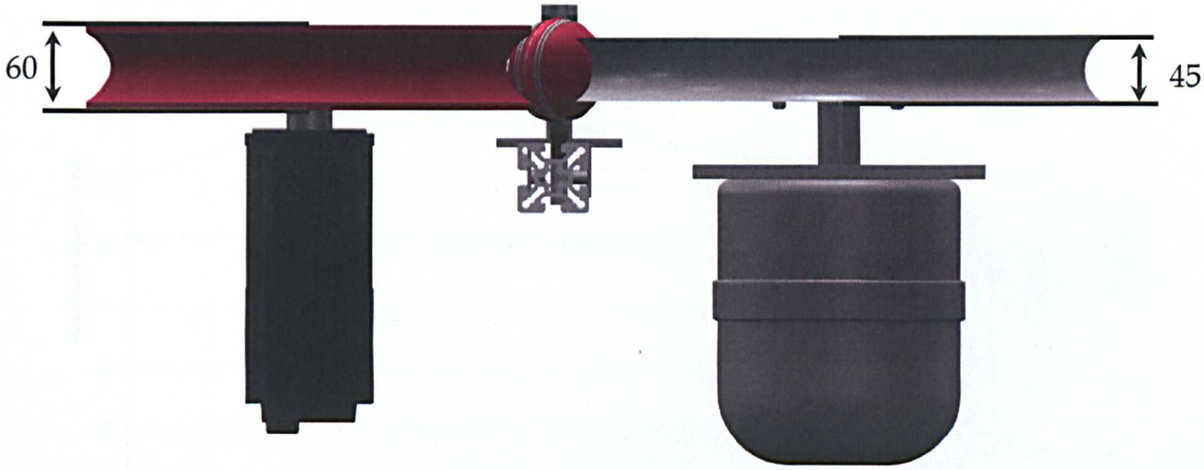


Figure 6.3.2: The new drive wheel design (left) vs. the first generation prototype wheel (right).

The first generation wheels had a fixed wheel separation of 51 mm, the distance between the apex of the concave profiles of the two wheels (see figure 6.3.3). Due to the alteration of the concave profile seen in the second generation drive wheels it was important to clarify their optimum separation.

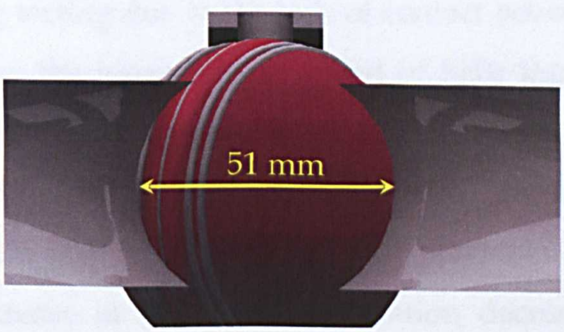


Figure 6.3.3: The measurement of wheel separation.

The driving wheel separation was tested with respect to the rotational wheel speed and the corresponding ball speed. The ball release speed was measured for five wheel separations (50, 55, 60, 65 and 70 mm) and four drive wheel speeds (1800, 2000, 2200, 2400 rpm). For this testing the spin head was stationary with the rollers positioned such that the scallops were aligned with the barrel. Each delivery in the 5 x 4 matrix was carried out five times and the mean results of testing are presented in figure 6.3.4.

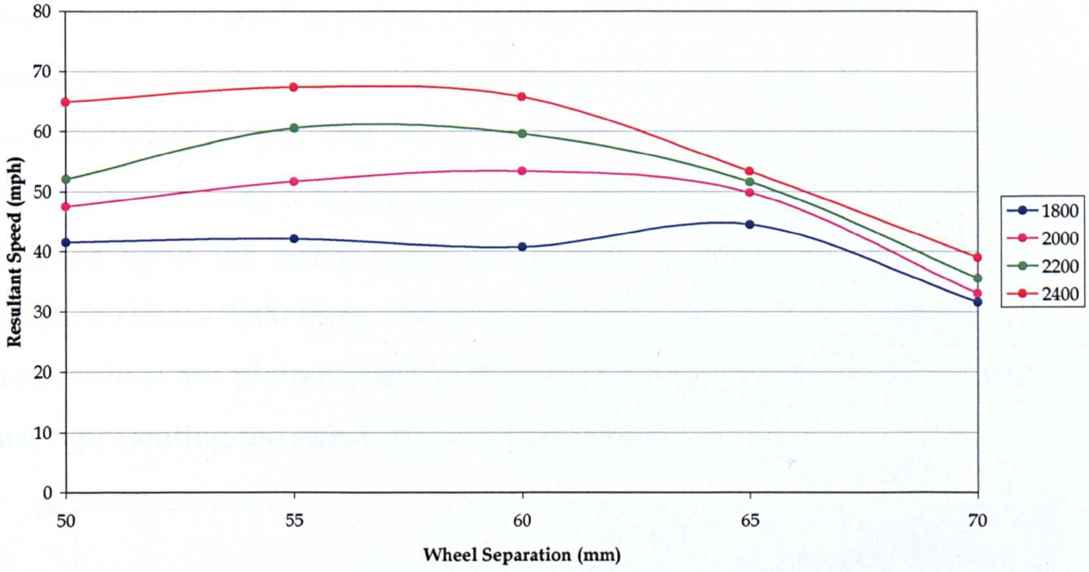


Figure 6.3.4: Measurement of ball release speed using five wheel separations and four wheel speeds.

The diameter of the ball used for the testing was 72.0 mm. It is therefore unsurprising that a wheel separation of 70 mm produced the slowest ball speeds seen during testing due to the lack of contact between the wheels and the ball. Comparing the mean release speed of balls input using 2400 rpm drive wheels at 70 mm separation (39.1 mph) and at 55 mm separation (67.7 mph) confirms the importance of identifying the most efficient drive wheel separation. On inspection of the data displayed in figure 6.3.4 the ball release speeds increase as the wheel separation decreases up to 55 mm separation. The ball release speed then tails off for deliveries output using a 50 mm drive wheel separation. From the shape of the curve displayed in figure 6.3.4 the wheel separation could have been chosen between 55 - 60mm. It was decided that 55mm should be the separation to ensure close contact with the ball was maintained reducing the opportunity for rotational slip as the ball passed through the drive wheels and shear stress on the ball surface. It was additionally decided that a wheel separation of less than 75% of the ball diameter should not be used due to safety implications of the ball being compressed to a high degree as it was fed into the machine increasing the likelihood of material failure. A separation of 55 mm represents 76.4% of the ball diameter.

Once the drive wheel separation had been established at 55 mm it was then possible to evaluate the second generation machine's capability in terms of pace deliveries output. The resultant speed of balls output from the machine was measured using a high-speed camera set up orthogonally to the machine, focussed upon the initial flight of the ball. Ten drive wheel speeds were analysed (1800 – 3600 rpm). The results of testing are presented in figure 6.3.5, mean values are plotted (each point representing five deliveries) with error bars representing the standard error in the mean.

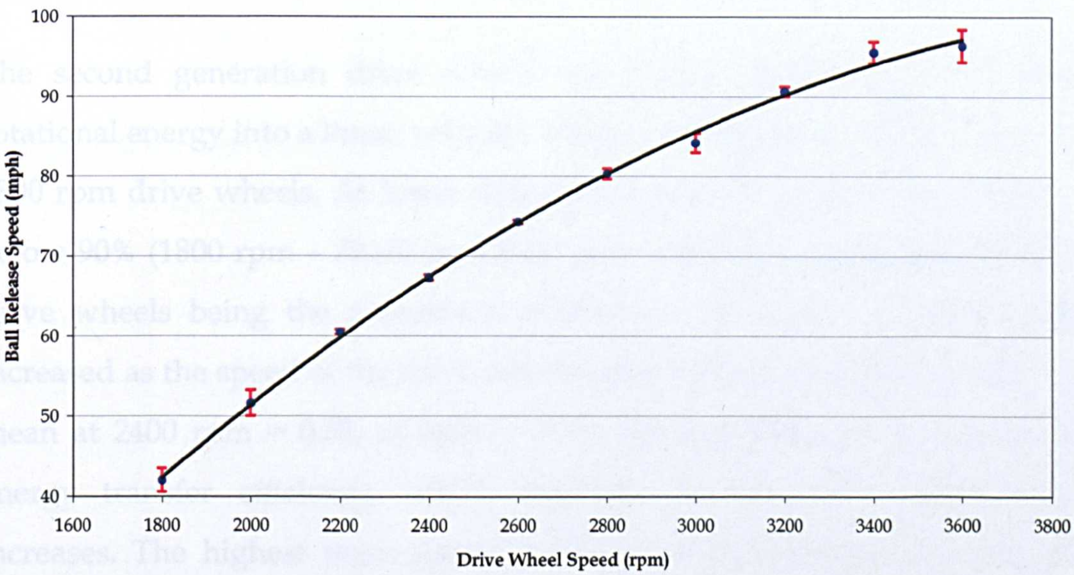


Figure 6.3.5: The release speeds of deliveries output using the second generation drive wheels with no spin head interaction.

The resultant speed of deliveries output from the machine increased approximately linearly up to 3200 rpm drive wheel speed. The mean ball release speed, standard error in the mean and energy transfer efficiency for the ten speeds analysed are presented in Table 6.3.1, the maximum release speed measured during testing was 102.3 mph (compared to 96.3 mph for the first generation machine).

Drive Wheel Speed (rpm)	Resultant Ball Speed (mph)	Standard Error in the Mean (mph)	Efficency %
1800	42.0	0.55	79.6
2000	51.6	0.87	88.0
2200	60.5	0.32	93.8
2400	67.3	0.33	95.7
2600	74.3	0.24	97.4
2800	80.3	0.69	97.8
3000	84.2	1.24	95.8
3200	90.7	0.63	96.7
3400	95.6	1.36	95.9
3600	96.4	2.01	91.3

Table 6.3.1: The performance of the second generation drive wheels.

The second generation drive wheels are highly efficient at transferring rotational energy into a linear velocity with a peak efficiency of 97.8% seen for 2800 rpm drive wheels. At lower drive wheel speeds the efficiency dropped below 90% (1800 rpm – 79.6% and 2000 rpm – 88.0%). In general, (3200 rpm drive wheels being the exception) variation in the speed of output balls increased as the speed of the drive wheels increased (i.e. standard error in the mean at 2400 rpm = 0.33, at 3600 = 2.01). The opposite can be said of the energy transfer efficiency, which decreases as the drive wheel speed increases. The highest mean speed measured was 96.4 mph for 3600 rpm drive wheels. This is not as fast as elite human performance has been recorded (Shoaib Akhtar 100.4 mph BBC Sport, 2002). For this experimentation the drive wheel motors were only capable of speeds up to 3600 rpm, however it is anticipated that once the motors can be rotated at greater speeds through gearing, all human pace deliveries will be achievable (see figure 6.3.6).

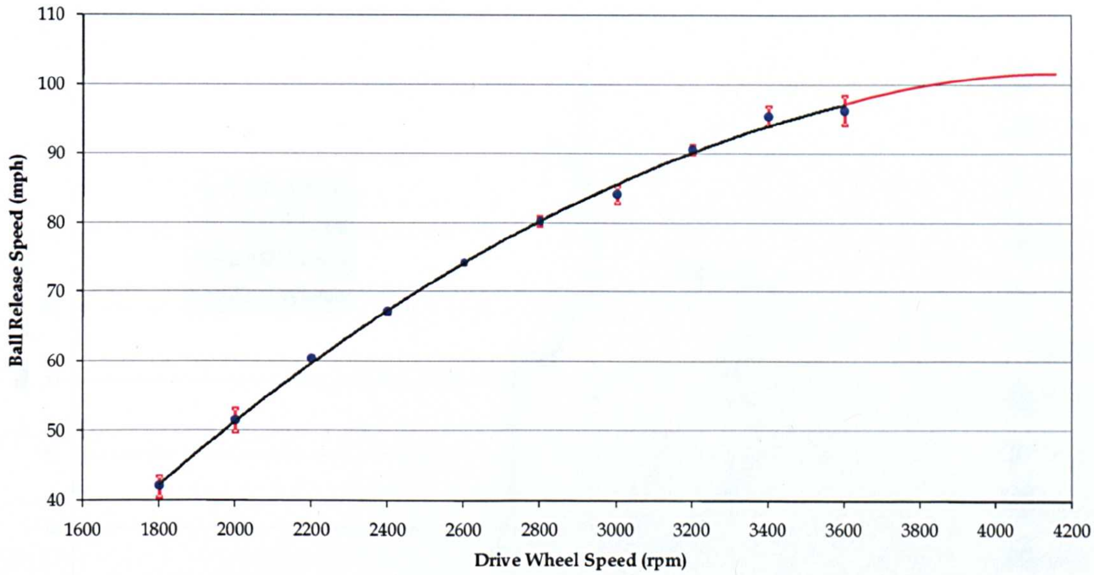


Figure 6.3.6: The anticipated release speeds of deliveries output using the second generation drive wheels with motor gearing.

The capability of the second generation machine to impart topspin and backspin was evaluated by measuring the speed and spin rate of balls output using offset drive wheel speeds. One drive wheel remained at a fixed speed while the other wheel speed was increased incrementally. For this testing the scallops of the spin imparting rollers were aligned with the barrel removing the spin head's influence on output deliveries. The results from this testing are presented in Figure 6.3.7: four fixed wheel speeds were used (1500, 1800, 2000 and 2200 rpm, represented by blue, red, green and orange data in Figure 6.3.7 respectively) and five trials were conducted at each of the incremented speeds. Increments started at 200 rpm faster than the fixed wheel speed, increasing up to 3600 rpm in 200 rpm increments.

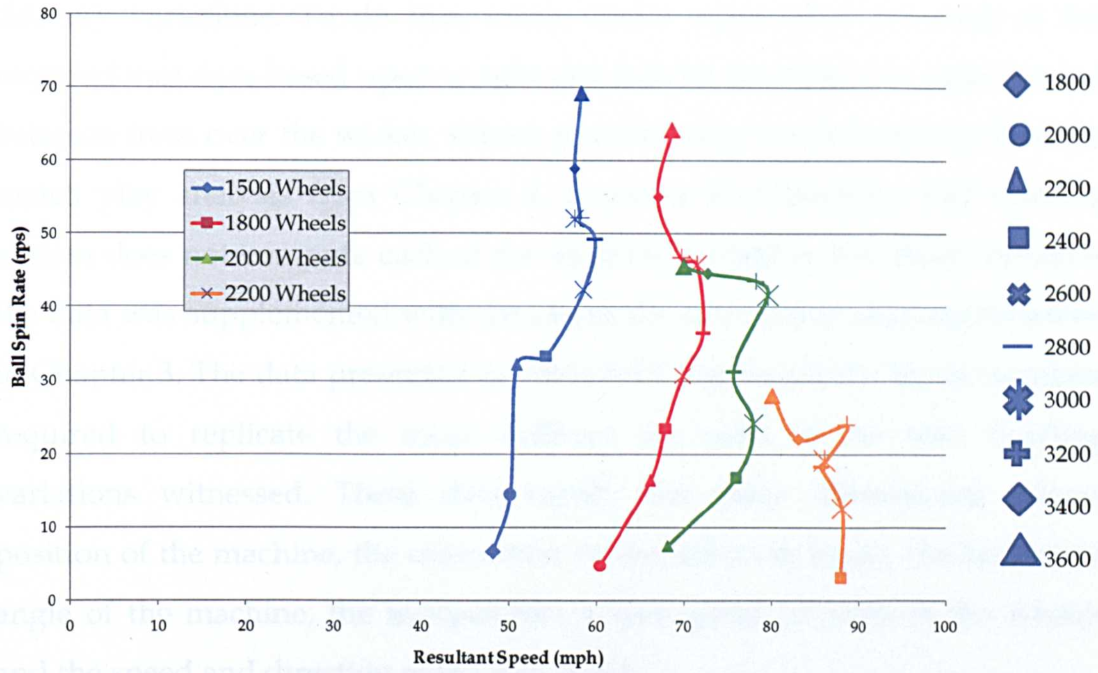


Figure 6.3.7: Ball speed and spin rates for deliveries output using offset drive wheel speeds.

Using offset drive wheel speeds the machine is capable of imparting spin rates of up to 69 rps onto the ball when wheel speeds of 1500 and 3600 rpm are used. When using 1500 and 3600 rpm wheel speeds the ball was released at 58.4 mph (mean). As the speed of the faster wheel was reduced, the speed and spin rate of the ball decreased. For example, when using faster wheel speeds (i.e. 2200 rpm left, 3600 rpm right) the resultant speed of the ball (80.2 mph) is reduced when compared to slower incremented wheel speeds (i.e. 2200 rpm left, 3000 rpm right = 86.3 mph). Additionally, the spin rate drops down to 7 rps when wheel speeds of 1500 and 1800 rpm are used.

6.4: Machine Input Variables:

The elite player performance analysis conducted in Chapters 3 and 4 developed a set of output variables for each of the delivery variations witnessed. This section will extend the data measured during the testing of spin head five and deliveries output using offset drive wheel speeds to establish the input variables required to reproduce each of the measured delivery variations. To do this, mean values were taken for each of the required variables based upon a right arm bowler bowling to a right handed batsman from over the wicket. Where possible, data was taken from the elite match play analysis from Chapter 4, however the HawkEye ball tracking system does not compute each of the required variables. For these variables the data was supplemented with data from the elite player analysis reviewed in Chapter 3. The data presented in Table 6.4.1 represents the input variables required to replicate the mean delivery for each of the spin bowling variations witnessed. These data signify the three dimensional release position of the machine, the orientation of the ball to be input, the horizontal angle of the machine, the independent wheel speed for each of the wheels and the speed and direction of the spin head.

	Release X	Release Y	Release Z	Ball Orientation	Launch Angle	Wheel Speed		Spin Head	
	Metres Wide of Centre Stump	Metres From Bowlers Stumps	Metres From Ground	Degrees From Normal	Degrees From Horizontal	Top (rpm)	Bottom (rpm)	Clockwise (rpm)	Anti-Clockwise (rpm)
Off Break	-1.03	1.06	2.25	53	4	2400	2400	X	2000
Leg Break	-0.24	1.21	2.02	-35.5	6.7	2600	2400	2000	X
Slider	-0.19	1.12	2	-31	6.9	2400	2000	2000	X
Flipper	-0.28	1.18	2.02	-79	0.1	1500	1900	X	X
Googly	-0.16	1.15	2.02	-49	5.8	2600	2200	X	3000

Table 6.4.1: The machine input variables required to replicate the mean delivery for each of the spin bowling variations seen during elite player analysis.

The data presented in Table 6.4.1 is based upon the input variables required for the second generation machine with spin head five to output the mean delivery for each of the variations. The data for the off break delivery was taken solely from the elite player analysis undertaken in Chapter 3. This is because the elite spin bowler analysed during match play in Chapter 4 was a wrist spin bowler who did not release an off break delivery. Hence there is a discrepancy between the variables measured mainly due to differences in technique (e.g. release speed) and size (e.g. release height (z)). It is however interesting to note the differences between the input variables required for a bowling machine to release an off break and a googly considering both deliveries are bowled by a right arm bowler and aim to deviate the ball in the same direction (to the right from a bowler's perspective). For the leg break, slider and googly deliveries the input drive wheel speeds have been set to impart topspin onto the ball prior to entering the spin head. This is due to the topspin element witnessed in each of these delivery variations seen in Chapter 3. For the flipper delivery the spin head is not employed as this delivery is imparted with backspin (see Chapter 3). The input drive wheel speeds for the flipper are slower than seen for the four other variations where, due to the spin head interaction with the ball, there is speed lost as the ball passes through the spin head.

The data presented in Table 6.4.2 represents the input variables required to replicate elite pace bowling performance. These data are concerned with the three dimensional release position of the machine, the ball orientation of input balls, the vertical angle of the machine and the independent drive wheel speeds required to release the mean delivery for each of the length variations seen. For these deliveries the spin head is not employed as none of the deliveries analysed were imparted with rifle spin.

	Release X	Release Y	Release Z	Ball Orientation	Launch Angle	Wheel Speed	
	Metres Wide of Centre Stump	Metres From Bowlers Stumps	Metres From Ground	Degrees From Normal	Degrees From Horizontal	Top (rpm)	Bottom (rpm)
Bouncer	-0.58	1.26	2.01	-5.9	-2.3	2400	2800
Short	-0.47	1.26	1.99	-5.9	-1.3	2200	2600
Back of a Length	-0.45	1.26	1.99	-5.9	-1.1	2200	2600
Length	-0.43	1.26	1.98	-5.9	-1.2	2200	2600
Full	-0.45	1.26	1.97	-5.9	-0.8	2200	2600
Yorker	-0.5	1.26	1.97	-5.9	0	2100	2500
Full Toss	-0.52	1.26	1.93	-5.9	-1.6	2300	2700

Table 6.4.2: The machine input variables required to replicate the mean delivery for each of the pace bowling variations seen during elite player analysis.

The data presented in Table 6.4.2 is largely derived from the elite match play analysis seen in Chapter 4. For the release position in the Y axis, 1.26 metres is quoted. The release position in the Y axis is not computed by HawkEye and this was the mean distance from the bowler's stumps measured for right arm bowlers from elite player analysis reviewed in Chapter 3. Additionally the ball orientation of -5.9 degrees from normal was the mean ball orientation for right arm bowlers measured from elite player analysis (see Table 3.6.6).

6.5: Machine Pitching Consistency:

The acquisition of new facilities within the Sports Technology Institute at Loughborough University meant that a cricket pitch sized enclosure was available for the testing of the bowling machine. One of the variables that had been difficult to measure previously due to time and space constraints on facilities was the pitching consistency of the machine. The new laboratory enclosure allowed the machine to be tested in house where there were no constraints on time and availability power as is the case at the National Cricket Academy in Loughborough. A full sized Cricket pitch was marked out on the floor of the facility and the machine was mounted onto a Rose and Krieger base frame and positioned at a height of 2.52 metres from the floor, above centre stump. As seen in the analysis of bowling performance in Chapters 3 and 4, the base of the centre stump at the bowler's (bowling machine) end represented the origin of the co-ordinate system used to take measurements from. A line was marked along the centre of the pitch with distance markers representing the distance from centre stump. Fifty balls were delivered from the bowling machine, ten rounds of five deliveries with the same five balls. The machine operator would manually input the balls using the manual input device (see figure 6.1.1) with the seam in an upright position at an angle of 0 degrees (see figure 3.6.1, Chapter 3).

Initial analysis was conducted using a series of three high-speed video cameras. The first camera sampled at a rate of 10,000 frames per second and was positioned orthogonally to the machine focussed upon the initial flight of the ball. A second camera (HSC 2, figure 6.5.1) was positioned above the intended pitching zone (15 metres from the centre stump) suspended on a beam at a height of 3 metres above the centre of the pitch. This camera would capture the ball as it made first contact with the pitch after release. A third camera (HSC 3, figure 6.5.1) was positioned orthogonally to the pitch at a distance of 15 metres from centre stump in the Y axis and -7 metres in the X axis. This camera was synchronised with camera 2 and captured the trajectory of each delivery prior to pitching. This enabled the position of pitching to be ascertained more accurately. Both cameras sampled at 500 frames per second. A grid was placed upon the floor covering the intended pitching zone for deliveries. This grid would act as an aid for taking measurements and made identification of pitching positions easier due to the red imprint left by deliveries which pitched upon the grid (see (b) figure 6.5.1).

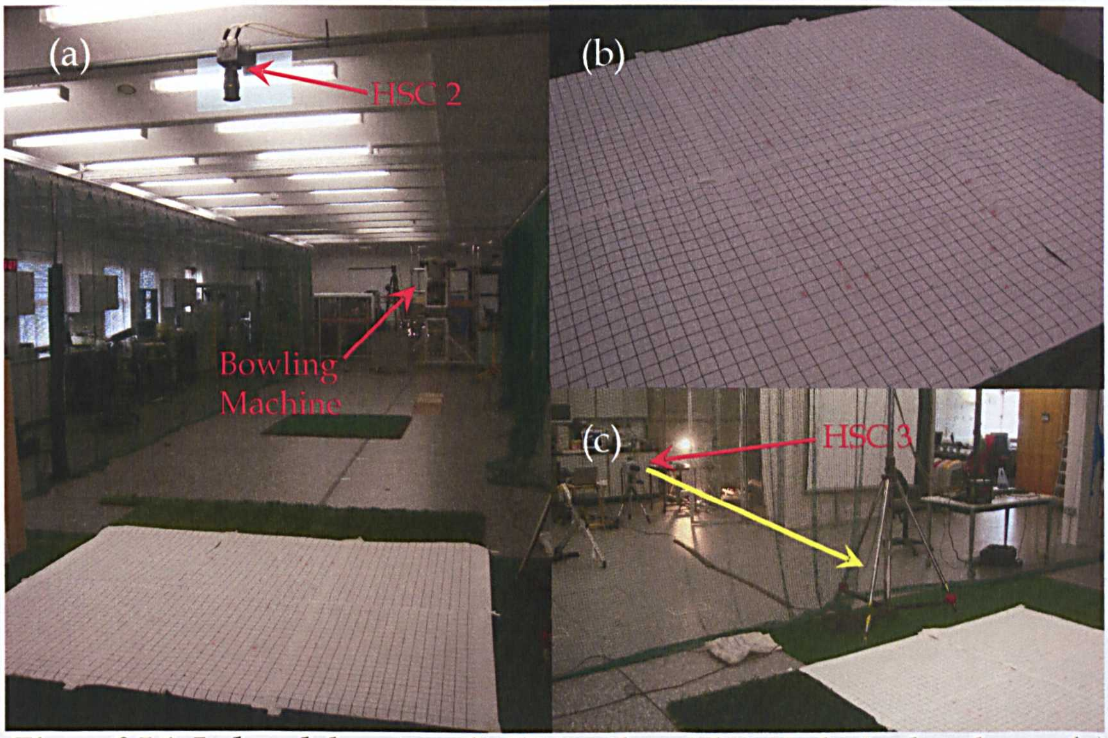


Figure 6.5.1: Indoor laboratory facilities; the cricket pitch sized enclosure (a), the intended pitching zone grid (b) and the third high-speed video camera capturing the ball trajectory (c).

Analysis of the machine's pitching consistency using high-speed video cameras had proved to be a time costly process where in addition to the time taken during testing downloading data there was also significant post processing of video data necessary to produce results.

The second generation machine was set up to release a delivery replicating the mean leg break (to right handed batsmen from over the wicket) bowled by the elite spin bowler analysed in Chapter 3. The mean pitching position of this delivery was 15.72 m from the bowler's stumps and 0.08 m wide of centre stump on the leg side. The pitching positions of fifty deliveries output from the second generation machine are plotted on a pitch map, figure 6.5.2. The mean pitching position is additionally plotted with error bars representing the standard error in the mean.

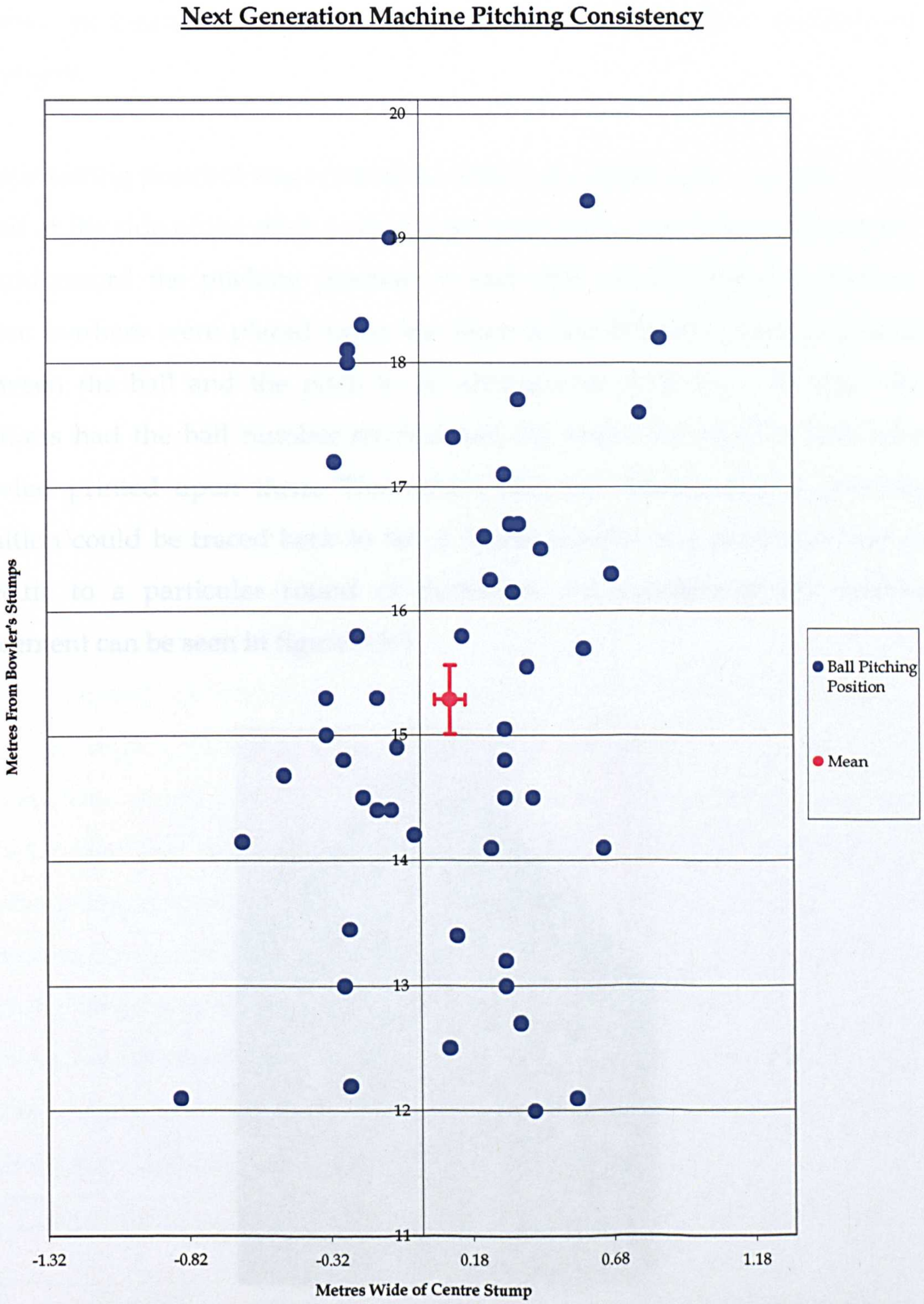


Figure 6.5.2: The pitching positions of fifty deliveries output from the second generation machine measured using high speed video analysis.

The results presented in figure 6.5.2 of the machine's pitching performance were inconclusive. Twenty eight deliveries (56%) pitched between 14 and 17 m from the bowler's stumps. It had become evident from the machine's limited performance in terms of consistency that further testing was necessary.

A new testing protocol was established where an experienced cricketer would stand at the side of the pitch as deliveries were output from the machine and would record the pitching position of each ball using annotated markers. These markers were placed upon the floor at the first the point of contact between the ball and the pitch to an accuracy of typically ± 50 mm. The markers had the ball number bowled and the round in which it had been bowled printed upon them. This meant that any discrepancy in pitching position could be traced back to see if it was specific to a particular ball or specific to a particular round of deliveries. An example of the marker placement can be seen in figure 6.5.3.

Figure 6.5.3: The marking of pitching positions using annotated markers.

The pace of this process meant that a great number of deliveries were able to be manually recorded in a significantly shorter time than when previously using high-speed video.

The consistency of the machine has been evaluated against the performance of competitor ball launching mechanisms and machines. Each of the competitors was tested in the same manner as the second generation bowling machine i.e. fifty balls released as ten rounds of five balls with an experienced cricketer placing annotated markers on the pitch at the position of ball pitching. In all, four competitors were evaluated for consistency: (i) a BOLA cricket bowling machine, (ii) Merlyn, a prototype cricket bowling machine specialising in spin bowling, (iii) Iron Mike, a baseball pitching machine that had been altered for cricket use at the National Cricket Centre, Loughborough, (iv) an air cannon was also tested for its consistency, this is a system used in a number of cricket bowling machines, notably manufactured by Kanon. Each of these ball launching devices have been described in detail in Chapter 2, section 2.6. Finally the first generation prototype machine was also evaluated. In addition, fifty deliveries from the two elite bowlers analysed during Chapter 4 were compared. The pitching data for these players was sourced from the HawkEye data sampled during the 2006/7 Ashes series. For the spin bowler fifty leg breaks bowled to batsman R3 during a single spell are analysed. For the pace bowler, fifty length and full deliveries bowled to batsman L2 are analysed. These lengths were used as the pitching lengths of the machines previously tested had spanned these two delivery length classifications. The mean pitching length and width for each of the systems and the two elite bowlers are presented in table 6.5.1 along with the standard error in the mean values.

N=50	Pitching Width (X)	Std. Error	Pitching Length (Y)	Std. Error
	Metres Wide of Centre Stump	Metres	Metres From Bowler's Stumps	Metres
First Gen.	0.023	0.0389	15.788	0.1790
Bola	0.019	0.0258	16.063	0.0397
Iron Mike	-0.325	0.0187	16.068	0.1690
Air Cannon	-0.025	0.0216	14.872	0.1493
Merlyn	-0.095	0.0855	16.205	0.1942
Second Gen.	-0.067	0.0469	14.449	0.5094
Second Gen. No Spin Head	0.107	0.0536	15.286	0.2708
Spin Bowler	-0.110	0.0340	15.437	0.1032
Pace Bowler	0.146	0.0256	14.477	0.1484

Table 6.5.1: The mean pitching consistency of the six bowling machines and two elite bowlers for fifty deliveries each.

Each of the machines were set to pitch at a "good length" releasing deliveries at around 55 mph. The pitching length and release speed was clearly not controllable for the two elite players analysed, however it is important to benchmark the performance of each of the machines against elite human performance. The mean pitching lengths seen during testing span 1.756 m, this would mean that the deliveries would span two delivery length classifications if evaluated in the same manner as pace deliveries in Chapters 3 and 4 (see Tables 3.6.8 and 4.1.3) where "length" deliveries span 0.98 and 1.65 metres respectively. The focus of this analysis was the consistency of pitching however, not how easy each machine was to aim at a target length. The standard error in the mean values presented in Table 6.4.1 are therefore of interest as it is these values that provide information on the consistency of each machine.

The pitching consistency of the second generation machine with spin head compares favourably to the other machines tested in terms of *pitching width.* Although a figure of ± 0.0469 metres is the second largest of the group, it is still representative of a high level of consistency. The pitching length of deliveries bowled by the second generation machine with spin head is inconsistent. A standard error in the mean value of ± 0.51 m is substantially greater than any of the other systems tested (± 0.19 metres next largest) and represents a high level of inconsistency in the pitching length of deliveries. The most consistent machine in terms of pitching length was the BOLA machine with a standard error in the mean value of ± 0.04 metres. It must be noted however that the BOLA machine is essentially a pair of counter rotating wheels, there is no spin imparting element to the machine and hence a higher level of consistency would be expected. The second generation machine was tested without the spin imparting head to establish the effect of the spin head on pitching performance. The standard error in the mean value for pitching length was significantly reduced by 46.8% to ± 0.27 metres (see Table 6.5.1) suggesting that the spin head has a significant effect on pitching length. This is an area that must be addressed in further work. It is interesting to note that the three machines that impart spin onto the ball (first generation, Merlyn and second generation) produced the three least consistent results in terms of pitching length, however the elite spin bowler produced the second best pitching length consistency demonstrating the high level of repeatability and control the bowler has over the ball (see Table 6.5.1).

The results of the pitching consistency testing are presented in figure 6.5.4. Mean values are plotted (each point representing fifty deliveries) with error bars representing the standard error in the mean.

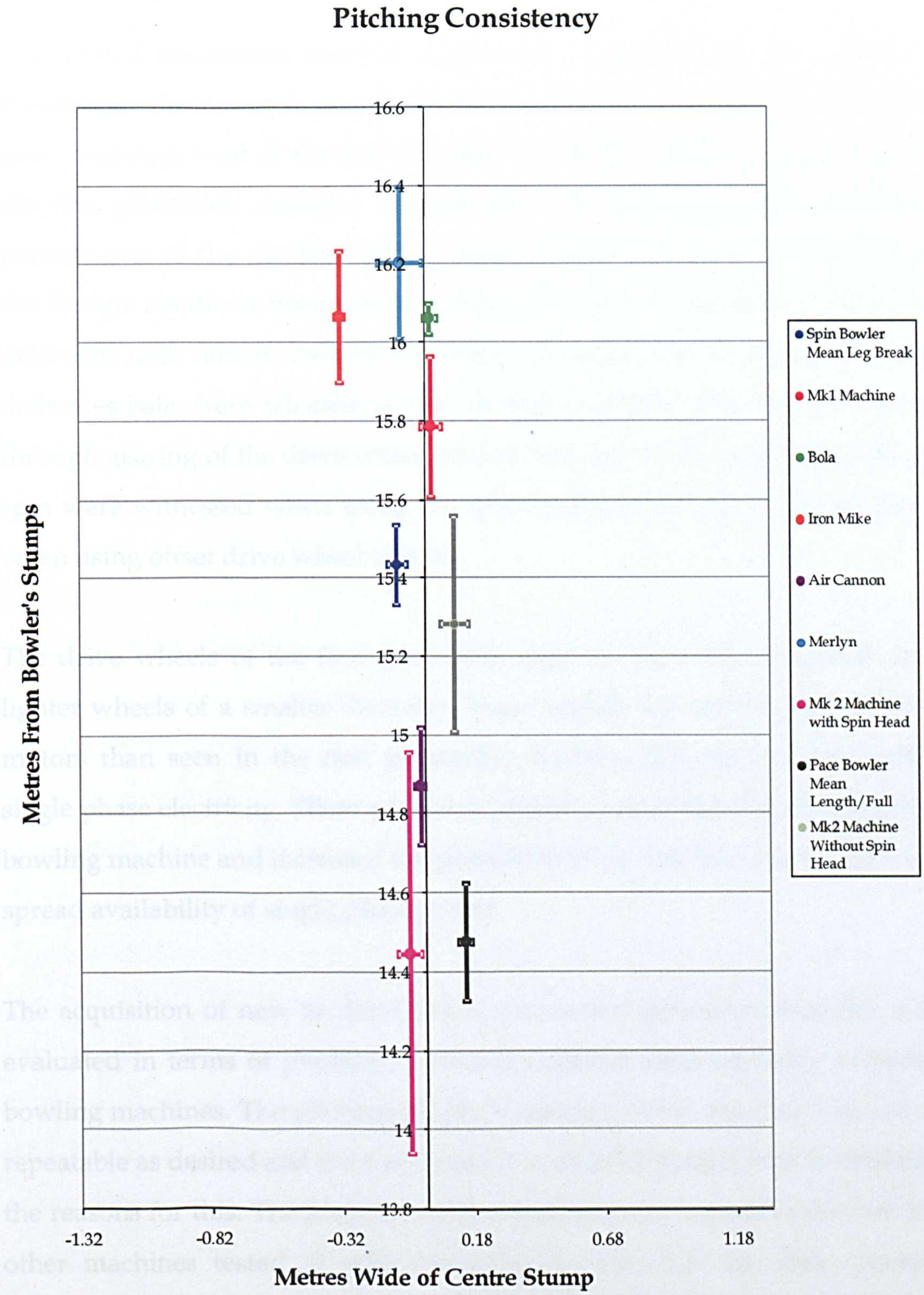


Figure 6.5.4: The mean pitching positions of six bowling machines and two elite bowlers. Error bars represent the standard error in the mean.

6.6: Conclusions

The second generation machine underwent a series of design alterations throughout the research project. These alterations were focussed upon the spin imparting head of the machine that was the significant step away from the first generation machine. At each stage the speed and spin imparting performance of the machine were evaluated with spin head five, the last of the design iterations documented within this thesis, capable of outputting deliveries with human realistic ball flight characteristics imparted. For pace deliveries balls were released at over 98 mph with this predicted to increase through gearing of the drive wheel motors. Spin rates of over 40 rps of rifling spin were witnessed when using the spin head and 69 rps of top/backspin when using offset drive wheel speeds.

The drive wheels of the first generation machine have been replaced with lighter wheels of a smaller diameter. These wheels are driven using smaller motors than seen in the first generation machine that are powered using single phase electricity. These additions have decreased the overall size of the bowling machine and increased the portability of the machine due to the wide spread availability of single phase power.

The acquisition of new facilities meant the second generation machine was evaluated in terms of pitching consistency against other currently available bowling machines. The pitching length consistency of the machine was not as repeatable as desired and the continuation of research should look to establish the reasons for this. The pitching width consistency was comparable with the other machines tested. It was interesting to note that the three poorest pitching consistency results were recorded by the three machines that imparted spin onto the ball, yet the elite wrist spin bowler was the second most consistent performer.

7: Ball Feeder Development

If a batsman is to be able to train efficiently he must be able to work alone without requiring additional resource to feed and orientate balls. Hence a next generation bowling machine must be able to input balls without any contribution from a machine operator. The bowler's grip on the ball in cricket is the clearest differentiator between delivery variations (see Chapter 2, section 2.3) as it determines the orientation and (coupled with the wrist and finger action) spin imparted onto the ball. In addition, pace bowlers hold the ball specifically to manipulate aerodynamic forces causing lateral deviation in flight (see Chapter 2, section 2.4).

In order to accurately recreate cricket bowling, it is therefore important that the ball is oriented and inserted into the machine correctly. Previous experimentation by Justham (2007) concluded that there is an optimal input speed (2.5 m/s) to reduce rotation of the ball on contacting the drive wheels. This is imperative if the ball is to enter the spinhead in the intended orientation for each selected delivery type.

The validation testing of a novel cricket bowling machine design has concluded that the machine is capable of imparting a high level of spin onto cricket balls with realistic spin bowling speeds (see Chapter 5, figure 5.2.28), however there is an inconsistency seen in pitching length (see figure 5.4.4). This has been attributed to the ball contacting the rollers at varying points when travelling through the spin head and losing both spin and forward energy in the process. The obvious hypothesis being that a greater level of contact between the rollers and the ball will result in a greater amount of speed lost from the ball and a shorter pitching delivery. In order to improve this, an automated input mechanism was sought such that the ball could be input into the spin head in a *known orientation* at a *known time*, synchronised to a *known position* within the rotation of the rollers (see Chapter 5). This would then allow for a consistent level of contact between the ball and rollers controlled by the point of ball insertion between the drive wheels. Prior to a ball being input between the drive wheels, it is fundamentally important to orientate the ball correctly for the delivery type selected. A next generation bowling machine must therefore be able to analyse cricket balls and identify the orientation of the ball seam prior to re-positioning the ball into the desired orientation. The research presented within this Chapter has been undertaken to address the following research questions:

- What steps are necessary to transform a randomly oriented cricket ball into a known orientation?
- What methods could be used to detect the position of the cricket ball seam?
- How can the orientation of the seam be determined?

7.1: Ball Feeder Conceptualisation:

In order to recreate realistic deliveries the orientation in which balls are released from the machine is an important variable (see Chapter 3). If the orientation of balls *released* from the machine is to be controlled, the orientation in which they are *input* must also be controlled. The operation of the machine currently requires human input to control the orientation and speed that balls are fed (see figure 5.1.1). If the training system is to operate efficiently, then the machine must be able to output deliveries without the input of a machine operator.

To this end, a number of ball feeding mechanism designs have been conceptualised. The requirement of a ball feeding system is that it can take a ball, analyse the ball's orientation and manipulate the ball into the desired orientation for the delivery type selected before inputting it into the machine (i.e. fed into the drive wheels). One such concept design is illustrated in figure 7.1.1.

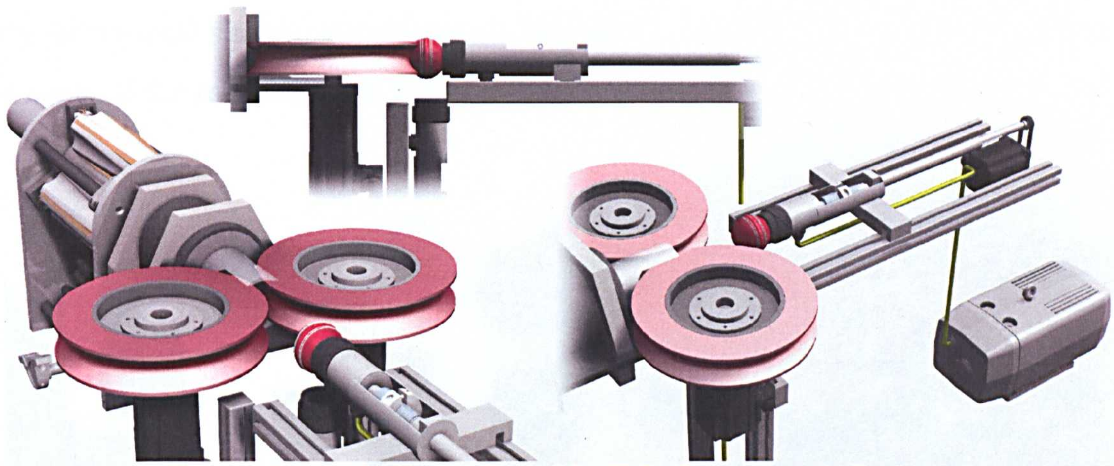


Figure 7.1.1: CAD generated ball feeder concept design.

The design featured in figure 7.1.1 uses an air vacuum and a suction cup with a foam insert to hold the ball securely. The foam insert is crucial if the ball is to be held securely as it moulds around the protruding seam of the cricket ball reducing a loss of suction incurred by using solid suction cups. The vacuum would be created using an electrically powered vacuum generator that sucks air in through the suction cup via an air hose connected to the feeder unit. The suction cup could be rotated using a small motor with a planetary gearbox and positional control achieved using an encoder on the back of the motor. Two identical manipulation units are envisaged, one would move in a horizontal plane, the other a vertical plane. The intention is that a hopper of balls would be housed as near to the ground as possible within the machine, helping to maintain the centre of gravity as low as possible. The vertically moving suction cup would drop into the hopper, activate suction and secure a ball in the suction cup, this would then move upwards towards the horizontally moving suction unit. Both suction cups can rotate about their axis of linear motion. The vertically moving suction cup would rotate the ball about the vertical axis (see 1, figure 7.1.2) allowing it to be analysed by, for example, a displacement gauge to enable the orientation of the ball to be determined. Once the seam orientation is known the ball can be manipulated into any desired position using a combination of rotations about the horizontal and vertical axes (see 2, figure 7.1.2). The final stage would be for the horizontal suction cup to secure the ball and insert it between the driving wheels of the machine (see 3, figure 7.1.2).

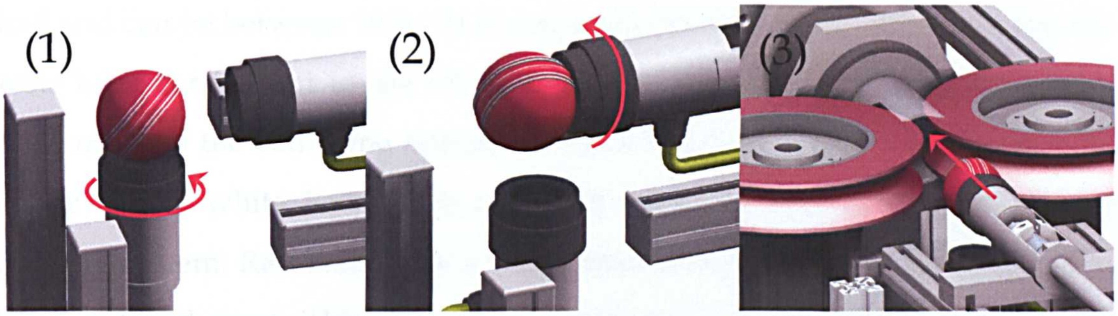


Figure 7.1.2: Proposed method of ball manipulation. 1: Rotation about the vertical axis. 2: Rotation about the horizontal axis. 3: Ball inserted between the drive wheels.

7.2: Determining the Position of a Cricket Ball Seam

Experimental work conducted to determine the position of a randomly oriented cricket ball seam is detailed in this section. The research is focused upon two methods of determining the position of the cricket ball seam. The first is an optical method analysing images of balls taken under controlled light conditions. The second method uses a tactile sensing process to detect the seam and determine its orientation.

The stages in which a ball would be analysed prior to being input into a bowling machine are summarised in figure 7.2.1. The key to successfully input of the ball into a machine in the correct position is the detection of the seam and the determination of its orientation. Hence the research presented has focussed upon this area prior to the implementation of an input mechanism.

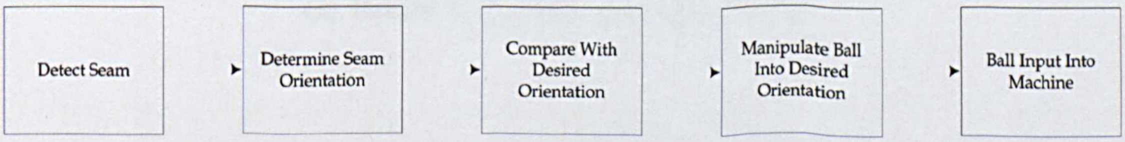


Figure 7.2.1: The steps taken to input the ball in the correct orientation.

7.2.1: Optical Method:

The seam of a cricket ball protrudes 0.5 - 0.8 mm above the leather surface of a ball and can be between 19.5 - 21.0 mm wide (BS 5993:1994). A series of initial tests were carried out to see whether the seam could be distinguished from the surface of the ball using optical methods. Cricket matches are played with either red or white balls, both of which must be used in a novel cricket training system. Red balls have a white stitched seam and white balls have a black stitched seam. This presents a challenge for vision based systems that rely upon contrast to distinguish between features as red balls have a lighter coloured seam than the leather surface of the ball and white balls have a darker seam then the leather surface of the ball. Thus a vision system would be required to depict a light element from a dark back ground (red ball) and a dark element from a light background (white ball).

Initially images were taken of a number of balls under various light conditions to identify the best environment for isolating the seam. These conditions were visible light, polarised light, infra-red light and backlighting. Images were taken of balls (both red and white) in a number of orientations, examples of which can be seen in Figure 7.2.2.

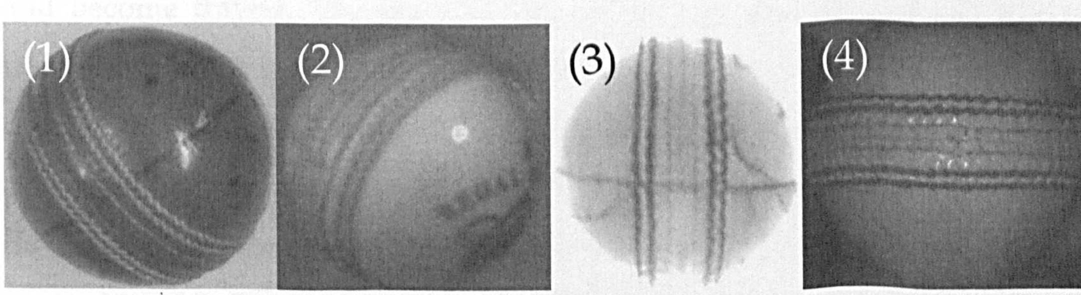


Figure 7.2.2: Images of balls taken under controlled lighting: (1) Red ball under visible light, (2) Red ball under infra-red light, (3) White ball backlit, (4) White ball under polarised light.

The results of this initial investigation concluded that infra-red lighting produced the best results as under infra-red conditions the red leather of red balls appeared lighter than the white seam of the ball (see (2) figure 7.2.2). This would mean that for both red and white balls the seam would appear darker than the leather of the ball. Initial images were captured of new or good conditioned balls, however further testing of older or worn balls uncovered an additional problem. As the ball ages the seam often deteriorates becoming less pronounced, torn or altered in colour. Images of two such examples are presented in figure 7.2.3.

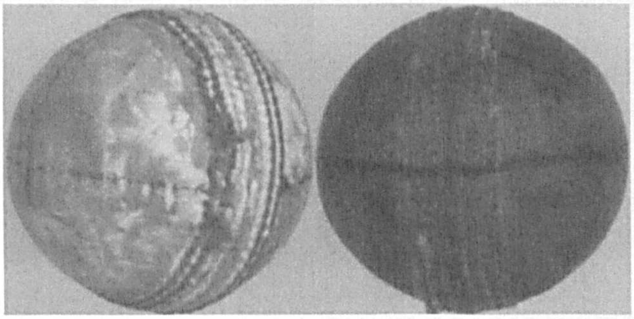


Figure 7.2.3: Two older, worn balls with visible deterioration of the seam, a white example (left) and a red example (right).

The two examples pictured in figure 7.2.3 exhibit typical ball deterioration. The leather of the white ball has become discoloured and the seam has torn and become frayed. The seam of the red ball has become less pronounced from the surface and it has become darker in colour making it difficult to distinguish from the leather of the ball with the human eye. These defects present difficulties for a vision system as the contrast between the seam and the leather surface of the ball is significantly reduced and the shape of the seam altered in the case of the white ball in figure 7.2.3.

Provided these difficulties could be overcome and the seam of the ball detected, there are further issues with a vision based method when determining the position of the seam. By creating an axis from the extremities of the centre seam through the centre of the ball ((i) figure 7.2.4) it is possible to identify the level of rotation ((ii) figure 7.2.4) necessary to manipulate the ball into the desired orientation ((iii) figure 7.2.4), in this case rotating such that the seam is vertical. Once this is complete, the second stage is to rotate the ball about a second axis to complete the transformation into the desired orientation. The distance x (iv, figure 7.2.4) is the distance measured from the centre of the ball to the apex of arc created by the seam detection line along the centre seam. This distance equates to the level of rotation required to complete the ball orientation.

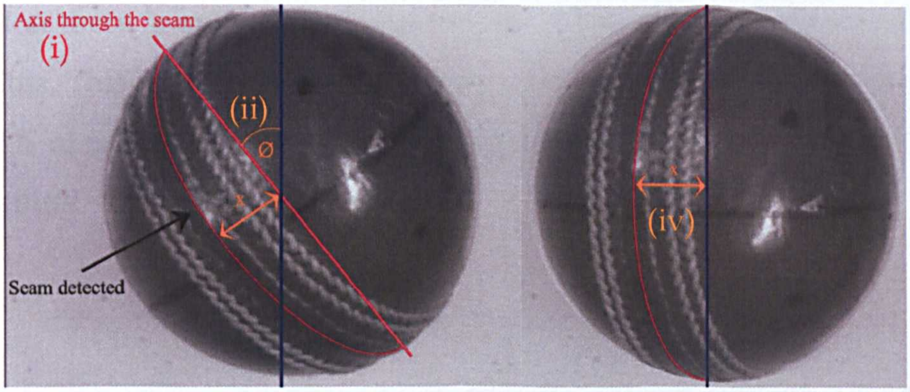


Figure 7.2.4: The steps of ball transformation.

The measured distance x can be expressed as a percentage of the ball radius and compared to known values of ball rotation. Figure 7.2.5 is a graph of results taken from measuring the distance x (as a percentage of the radius) compared to the level of rotation from the desired orientation for three balls.

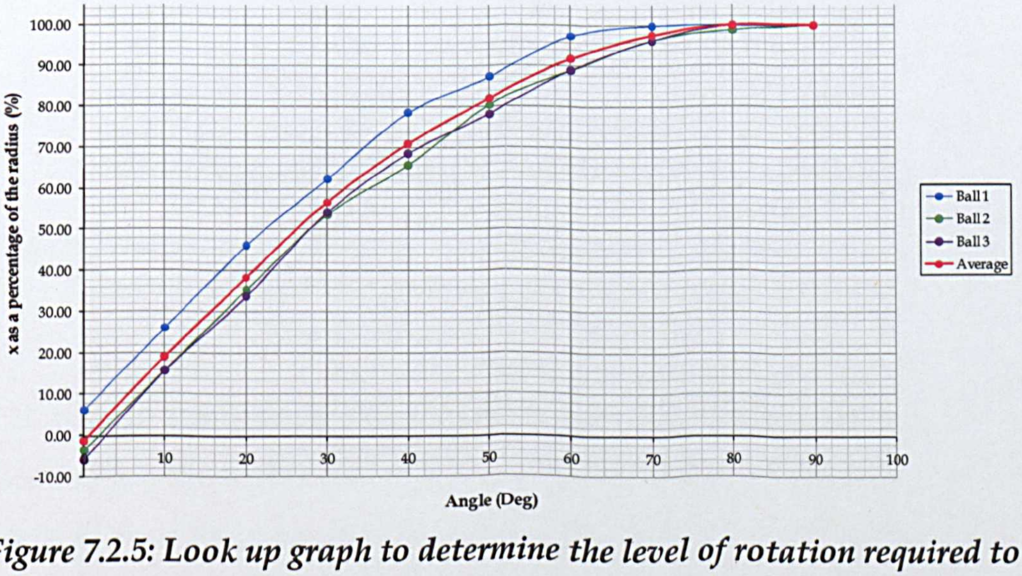


Figure 7.2.5: Look up graph to determine the level of rotation required to translate the ball into desired orientation based upon the distance x.

Using the average data from the three balls analysed (red line, figure 7.2.5) it is possible to predict the level of rotation required to reposition the ball as desired. For example if the distance x represented 40% of the radius distance, the required rotation would be 21 degrees. However, there is a problem with the data presented in figure 7.2.5. Although at low x values the required rotation is consistent, as the plane of the seam gets closer to parallel with the lens of the camera (i.e. closer to 90 degrees) it becomes increasingly difficult to distinguish between the level of rotation required. Between 70 and 90 degrees of rotation there is only a 3% change in the distance x as a percentage of the ball radius. This represents a significant loss in resolution from 0 - 40 degrees where 1% of radius = 0.56 degrees of rotation, however from 70 - 90 degrees, 1% of radius = 6.67 degrees of rotation.

7.2.2: Tactile Sensing Method:

Due to the issues witnessed with optical analysis a tactile sensing method of determining the orientation of cricket ball seam was sought. Initial testing was conducted using a digital displacement gauge (MAHR Millitast 1075) positioned such that the probe was in contact with the surface of the ball (see figure 7.2.1). The ball was held in a bespoke cup attached to a stepper motor used to rotate the ball. A Visual Basic programme was written to control the stepper motor from the PC, interface to the digital dial gauge (via an RS232 serial link) and output the displacement readings from the gauge as a function of stepper motor position to a Microsoft Excel file for analysis. The resolution of the stepper motor was 200 steps per revolution (1.8 degrees each step) and at each step a displacement reading was recorded.

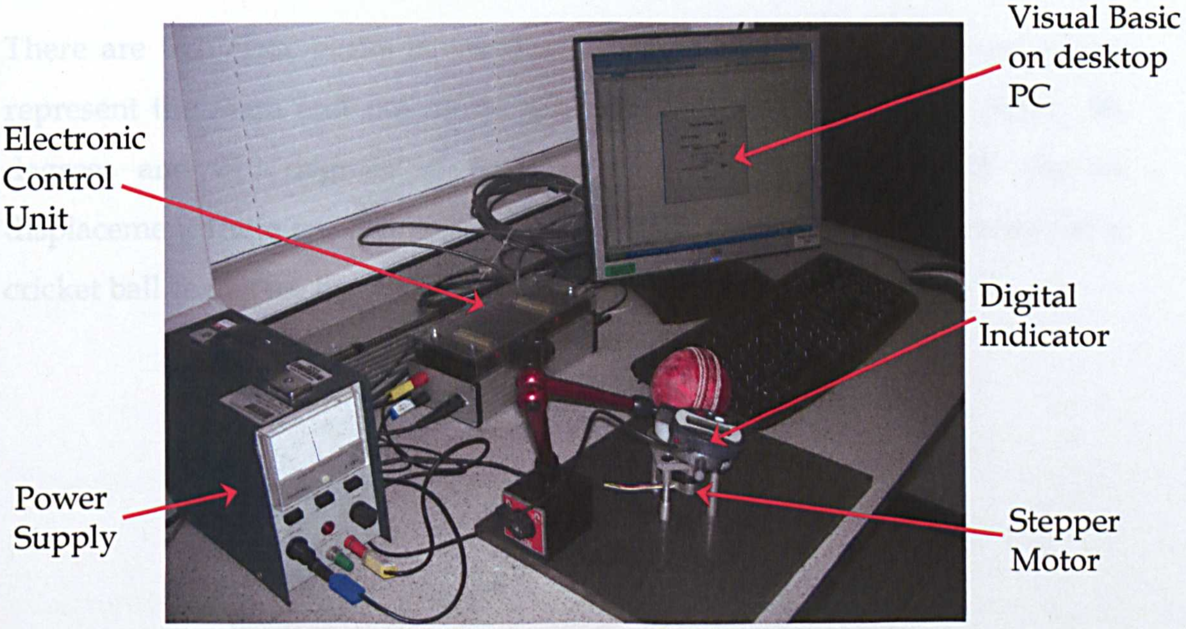


Figure 7.2.1: A ball held and rotated in the bespoke cup measured by the displacement gauge.

Initial testing was conducted with the displacement gauge positioned to record around the equator of the ball with the seam in an "upright" position. Recording was initiated with the seam perpendicular to the probe of the gauge and one complete revolution was recorded. The data was exported to Excel and the graph displayed in figure 7.2.2 produced.

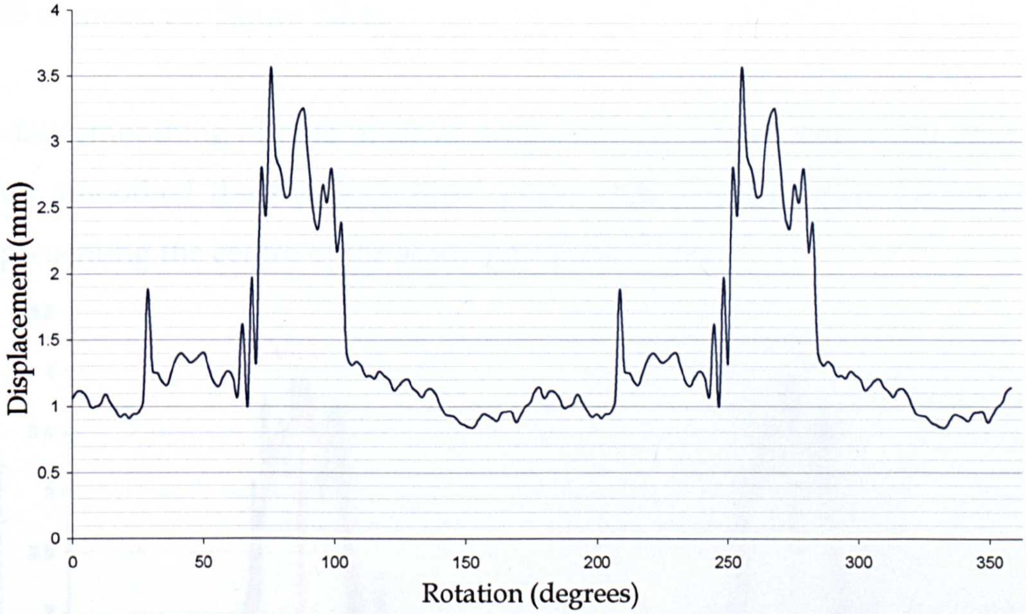


Figure 7.2.2: The displacement data produced from a complete ball revolution.

There are two clear peaks in the data presented in figure 7.2. These peaks represent the seam and the centre of the peaks appear at approximately 90 degrees and 270 degrees of rotation as expected. Within each rise in displacement there are five individual peaks, these represent the ridges of a cricket ball seam (see figure 7.2.3).

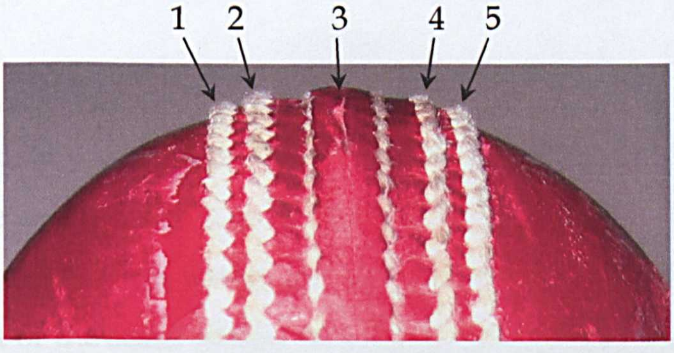


Figure 7.2.3: The five ridges created by the cricket ball stitching.

The data displayed in figure 7.2 indicates that the probe is in contact with the seam of the ball for between 35-40 degrees at each time, this equates to approximately 10% of the ball circumference and is representative of the seam width as a percentage of the ball circumference ≈ 9%. When orienting the ball it is however important to locate the *centre* of the seam as locating any edge of the seam could would result in an error in alignment (which could be up to ± 25 degrees, see figure 7.2.4).

A data smoothing filter (5 point moving average) was applied to the data. The filter smoothed the five individual peaks with the maximum displacement representing the centre of the seam (see figure 7.2.4).

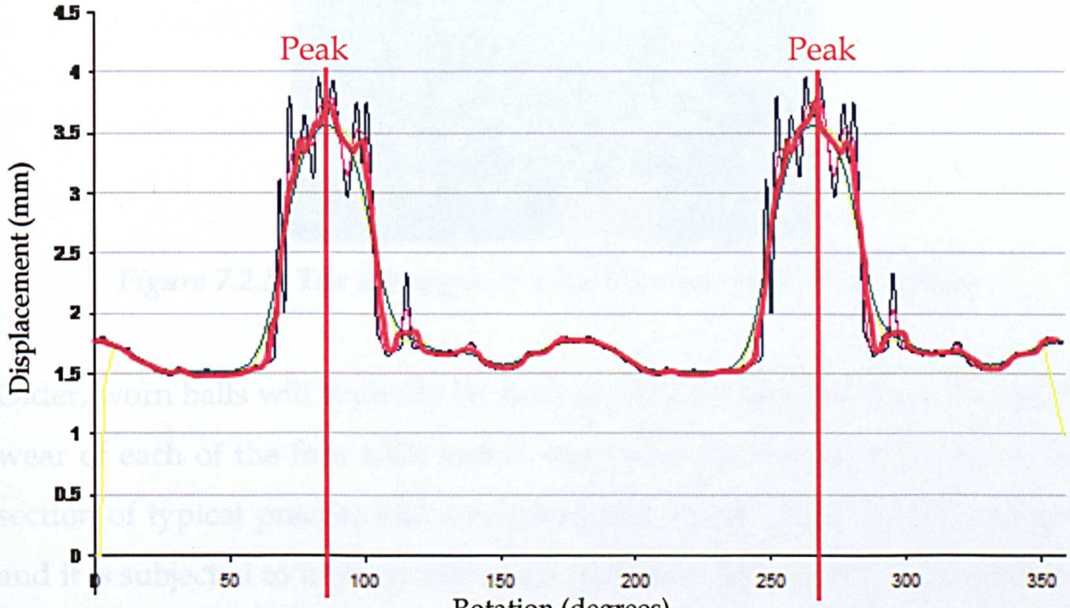


Figure 7.2.4: Smoothed displacement data with peaks representing the seam centre.

The smoothed data presented in figure 7.2.4 provides a clear indication of the position of the seam with respect to the ball's original orientation. The maximum value occurring within the first 180 degrees of ball rotation gave the centre point of the seam which, in the case of the data displayed in figure 7.2.4 is at approximately 90 degrees. However the system would also need to determine the position of the seam when it is not "upright" and thus a series of tests was conducted to analyse the capability of this method with the seam tilted to the vertical.

Balls were placed into the rotation cup and titled to known angles measured using a protractor (see figure 7.2.5). Four different balls at eleven tilt angles between 0 and 180 degrees were tested and measured five times each.

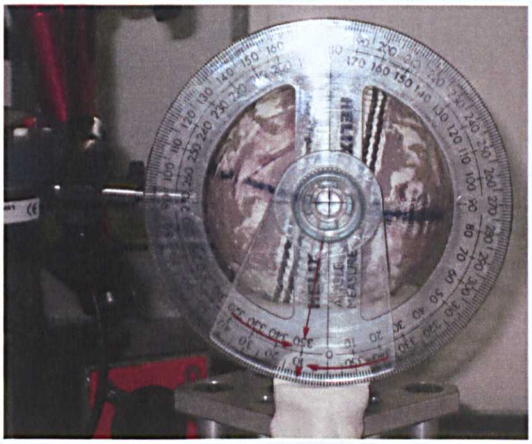


Figure 7.2.5: The tilt angle of a ball measured prior to testing.

Older, worn balls will typically be used in cricket training. Hence the age and wear of each of the four balls tested was varied to represent a realistic cross section of typical practice ball conditions (see figure 7.2.6). As the ball wears and it is subjected to impacts with both pitch and bat it can become deformed. It was therefore important to test the accuracy of the tactile method with balls of varying age and wear.

Figure 7.2.6: The four balls used during testing; 1: A white worn Readers, 2: A red new Readers, 3: A red worn Readers and 4: A red worn Slazenger.

The tilt angle of each ball was carefully measured and the performance of the system evaluated against these measurements. The angles included 90 degrees where the seam was horizontal and 180 degrees where the seam returned to upright (see figure 7.2.7).

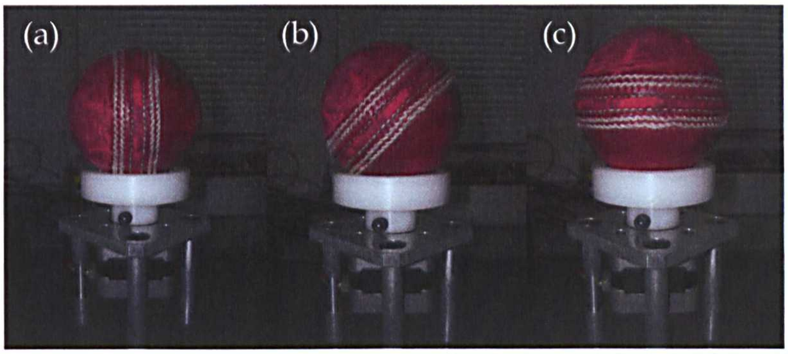


Figure 7.2.7: Three example tilt angles used in testing: (a) 0 or 180 degrees, (b) 30 degrees, (c) 90 degrees.

The resulting data from the 180 degree rotation ball scan was smoothed using the five point moving average filter and the maximum value/values determined. This value would then represent the necessary rotation of the ball from the starting point in order that the probe would lie on the centre of the seam. For this series of tests the orientation was such that the seam was initialised perpendicular to the probe of the displacement gauge. Thus a successful result would mean the seam was detected at 90 degrees. The results from testing are presented in Table 7.2.1. Mean values are quoted (representing five trials) for the four balls tested.

Start Angle 90	White Worn Ball 1		Red New Ball 2		Red Worn Ball 3		Red Worn Ball 4	
Tilt Angle (Deg)	**Detected (Deg)**	**Error (Deg)**	**Detected (Deg)**	**Error (Deg)**	**Detected (Deg)**	**Error (Deg)**	**Detected (Deg)**	**Error (Deg)**
0	87.8	-2.2	92.9	2.9	85.7	-4.3	88.6	-1.4
30	92.2	2.2	91.8	1.8	84.6	-5.4	90.7	0.7
60	90.7	0.7	94.0	4.0	88.2	-1.8	91.8	1.8
70	91.8	1.8	87.5	-2.5	87.5	-2.5	93.2	3.2
80	138.6	48.6	95.4	5.4	99.0	9.0	88.6	-1.4
90	131.0	41.0	48.6	-41.4	40.3	-49.7	140.0	50.0
100	60.8	-29.2	61.2	-28.8	34.2	-55.8	86.4	-3.6
110	109.8	19.8	46.8	-43.2	76.7	-13.3	84.6	-5.4
120	94.0	4.0	83.2	-6.8	85.9	-4.1	88.2	-1.8
150	90.4	0.4	86.0	-4.0	86.8	-3.2	87.1	-2.9
180	93.2	3.2	88.6	-1.4	91.4	1.4	92.5	2.5

Table 7.2.1: The level of ball rotation required to find the seam, as detected by the tactile sensing method.

It is clear from the data presented in Table 7.2.1 that the tilt angle of the seam has a great effect on the accuracy of this method. For tilt angles of 0 - 70 degrees and 120 - 180 degrees the system is accurate to within 8%, however when a tilt angle of greater than 60 degrees is present the error significantly increases. The difficulty is that the more the seam is oriented towards the horizontal the greater the amount of time that the probe is in contact as the ball is rotated. Hence it is more difficult to differentiate a peak associated with the displacement of the seam relative to the rest of the ball in the data. For example, in the extreme case when the tilt angle is at 90 degrees the probe tracks around the ball on the centre of the seam and does not detect the remaining surface of the ball at all. Nevertheless, theoretically the displacement should be equal throughout the ball rotation and this could be used as a signature of the orientation of the seam. However the situation is sensitive to any irregularities in the circumference of the ball and this could cause the displacement of the gauge to vary and result in an error in measurement i.e. an incorrect assumption of a random irregularity being due to the seam (see Table 7.2.1).

When the ball is oriented with a tilt angle of 90 degrees the probe is in contact with the centre seam for the entirety of the ball revolution. Employing the current algorithm the system will identify the point of largest displacement as the centre of the seam. These errors can be mitigated if the time (or angle) that the probe is in contact with the seam can be determined. A test was conducted to measure the effect of tilt angle on the contact time between the probe and the seam and the level of error in measurement allowable to still locate the seam. The number of steps the probe was in contact with the ball when positioned at eleven different tilt angles was recorded. These data are presented in Table 7.2.2 where the level of contact with the seam and the centre seam is reviewed, each figure representative of five trials.

Tilt Angle (Deg)	Steps in contact with the seam	Angle of rotation in contact with the seam (Deg)	Steps in contact with the centre seam	Angle of rotation in contact with the centre seam (Deg)
0	17	30.6	5	9.0
30	21	37.8	6	10.8
60	38	68.4	9	16.2
70	48	86.4	14	25.2
80	100	180.0	25	45.0
90	100	180.0	100	180.0
100	100	180.0	26	46.8
110	48	86.4	14	25.2
120	38	68.4	10	18.0
150	21	37.8	6	10.8
180	17	30.6	5	9.0

Table 7.2.2: The level of contact between the ball seam and displacement probe for a number of ball tilt angles.

The data presented in Table 7.2.2 confirm that as the tilt angle approaches horizontal, the seam and probe spend an increasing amount of time in contact with each other. The greater the time spent in contact with the centre seam, the higher level of error in measurement is allowable for the centre seam to still be identified as the number of points where the seam could still be found increases. However, when the seam is positioned with a 0 degree tilt angle the probe is only in contact with the centre seam for 5 steps, representing 9 degrees of rotation. This means that the level of accuracy required for the tactile system to find the centre seam is ±4.5 degrees (2.5% of the 180 degree revolution).

A further step was taken where additional Visual Basic code was written such that a ball would be scanned, the position of the centre seam located and the ball rotated so that the probe was positioned on the centre seam. In order to do this the code incorporated the sampling of the raw displacement gauge data, applied a five point moving average filter, detected the centre of the seam and rotated the ball accordingly. These steps are summarised in figure 7.2.8 with examples of the Visual Basic code additionally presented.

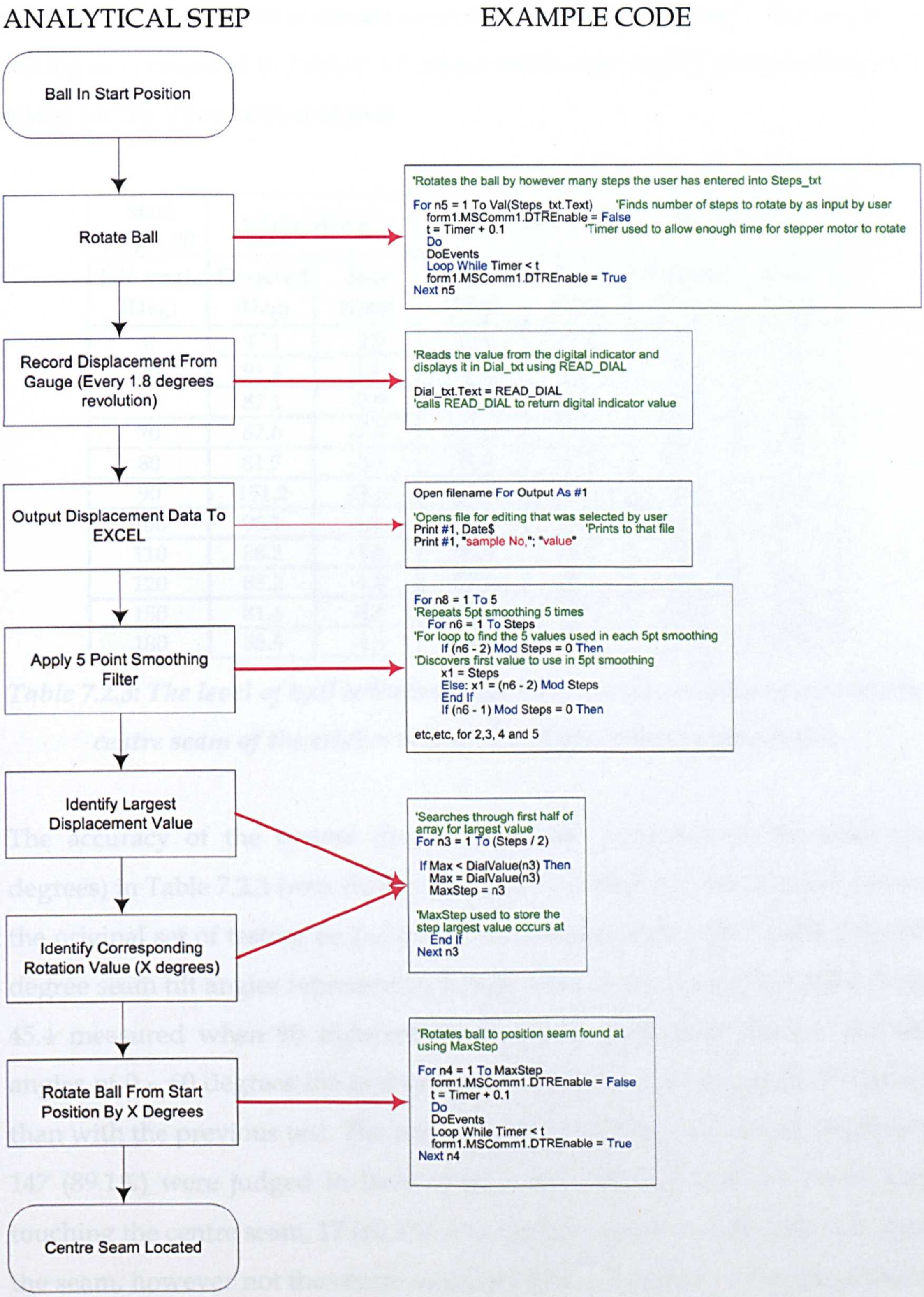


Figure 7.2.8: The analytical steps taken to determine the seam position presented with elements of the visual basic code.

Three balls were chosen for testing, balls 1, 2 and 3 (see figure 7.2.6). Ball 4 was discarded as it had a similar level of wear to ball's 1 and 3. The results of testing are presented in Table 7.2.3. Mean results are quoted (representing five trials) for the three balls analysed.

Start Angle 90	White Worn 1		Red New 2		Red Worn 3	
Tilt Angle (Deg)	Detected (Deg)	Error (Deg)	Detected (Deg)	Error (Deg)	Detected (Deg)	Error (Deg)
0	87.1	-2.9	88.6	-1.4	87.1	-2.9
30	91.4	1.4	87.5	-2.5	92.2	2.2
60	87.1	-2.9	88.9	-1.1	85.3	-4.7
70	82.6	-7.4	93.2	3.2	85.5	-4.5
80	81.7	-8.3	79.6	-10.4	82.8	-7.2
90	151.2	61.2	24.8	-65.2	45.4	-44.6
100	96.1	6.1	89.6	-0.4	90.4	0.4
110	88.2	-1.8	89.3	-0.7	85.7	-4.3
120	88.2	-1.8	87.8	-2.2	97.4	7.4
150	81.4	-8.6	86.8	-3.2	87.1	-2.9
180	88.6	-1.4	89.3	-0.7	87.1	-2.9

Table 7.2.3: The level of ball rotation required to automatically reposition the centre seam of the cricket ball on the displacement gauge probe.

The accuracy of the system (indicated by the reduction in the error (in degrees) in Table 7.2.3 from those presented in Table 7.2.1) has increased from the original set of testing on balls with tilted seams with only results from 90 degree seam tilt angles representing a high level of inaccuracy (i.e. 151.2, 24.8, 45.4 measured when 90 expected for the three balls respectively). For tilt angles of 0 – 60 degrees the highest error was 5.2%, approximately 3% lower than with the previous test. The test comprised 165 trials. Of those completed, 147 (89.1%) were judged to have rotated the ball such that the probe was touching the centre seam, 17 (10.3%) were judged to have rotated the ball onto the seam, however not the centre seam (an error of up to ± 4.5 degrees) and 1 (0.6%) was judged to not have found the seam.

It is anticipated that a system comprising two orthogonal displacement gauges would be needed to orientate the ball robustly (see figure 7.2.9). With this configuration the ball would be first rotated about the Z-axis (see 1, figure 7.2.9) and re-oriented as described in the previous experimentation. Once in a known position, the ball would be rotated about the Y-axis by a second cup (see 2, figure 7.2.9) to detect the seam and manipulate the ball into the desired orientation.

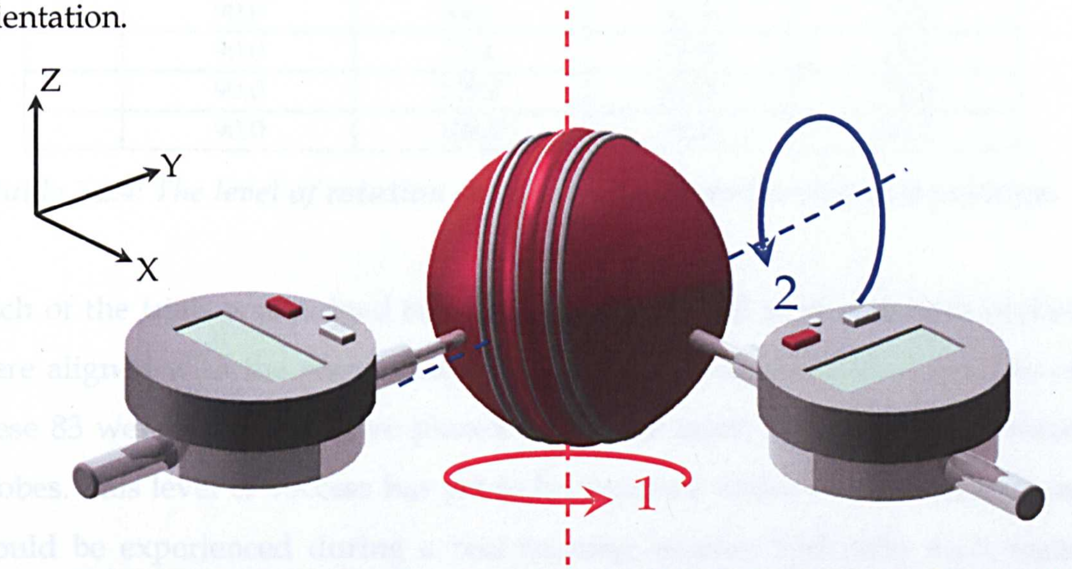


Figure 7.2.9: Method of orienting the cricket ball. Rotate about the Z-axis (1) and then the Y-axis (2).

A final investigation was carried out performing the two step orientation described above. Ball's 1 and 2 were selected (see figure 7.2.6) positioned at five tilt angles within the rotation cup with the seam starting perpendicular (90 degrees) to the first displacement gauge probe. The first displacement gauge measured the angle of rotation required to position the probe on the centre seam of the ball. This was carried out using the previously described method, rotating the ball about its Z-axis. The second gauge was employed to measure the level of rotation required to position the second probe on the centre seam, rotating about the Y-axis. The results of this testing are presented in Table 7.2.4, with the angle of rotation measured using the first displacement gauge and the tilt angle measured by the second gauge. Mean values are quoted, each representative of five trials.

Ball	Angle of Rotation (Deg)	Angle of Rotation Detected (Deg)	Tilt Angle (Deg)	Tilt Angle Detected (Deg)
Ball 1	90.0	88.2	0.0	0.3
White	90.0	82.8	45.0	39.6
	90.0	81.0	70.0	66.6
	90.0	83.0	80.0	75.6
	90.0	79.8	90.0	86.4
Ball 2	90.0	88.2	0.0	1.8
Red	90.0	84.6	45.0	46.8
	90.0	77.4	70.0	68.4
	90.0	109.8	80.0	79.2
	90.0	102.0	90.0	88.2

Table 7.2.4: The level of rotation calculated to determine the seam position.

Each of the trials was judged to have aligned the ball such that both probes were aligned with the seam. One hundred trials were conducted in total, of these 83 were judged to have placed the centre seam on both displacement probes. This level of success has yet to be repeated under time constraints as would be experienced during a real training session. Currently each seam orientation detection process takes approximately 50 seconds from commencing scanning to the point of seam identification and hence the total process would take approximately 2 minutes to complete. The main source of time delay is the download of displacement data from the gauge to the PC (taking approximately 12 seconds to download 200 data points. This is the result of the slow communication interface to the gauges (i.e. Baud rate of 9600) which is anticipated to be significantly increased using gauges with faster communication specifications.

The tactile sensing method described in this chapter results in the displacement probe placed upon the seam of the cricket ball. Figure 7.2.1 described the control sequence required in order to input a ball into a machine in a known orientation from an unknown orientation. Following the stages of the tactile sensing method described in this chapter, the ball is in a known orientation from which it can be manipulated into a desired orientation for each delivery type selected. Elite player analysis was conducted in Chapter 3, from which the orientation of the ball at release was measured for a number of delivery types. Following the tactile sensing method the ball is always in the same position; with the seam upright, parallel to the pitch (Zero degrees (see Chapter 3)). The data displayed in Table 7.2.5 quantifies the mean level of rotation from this position required to replicate the release conditions for each of the delivery types measured during the elite player analysis. Each of the deliveries witnessed were released with an upright seam and hence no rotation is required about the X and Y axes (see figure 3.2.6).

Delivery Type	**Rotation (Degrees)**		
	X	**Y**	**Z**
Right Arm Pace	0.00	0.00	-6.00
Left Arm Pace	0.00	0.00	-3.00
Right Arm Off Spin	0.00	0.00	53.00
Left Arm Orthodox	0.00	0.00	-45.00
Right Arm Leg Break	0.00	0.00	-36.00
Right Arm Slider	0.00	0.00	-31.00
Right Arm Flipper	0.00	0.00	-79.00
Right Arm Googly	0.00	0.00	-49.00

Table 7.2.5: The level of rotation required to translate the ball from a known position defined during the tactile sensing method for each of the delivery types measured during elite player testing.

Although none of the deliveries measured during elite player testing required translation about the X or Y axes, it is anticipated that some deliveries would require this, particularly for wrist spin bowlers where orientation of the ball at release can vary due to the manipulation of the wrist position. The data presented in Table 7.2.5 are mean values measured from video data. It is anticipated that a database of deliveries would be created in which the orientation of the ball at release would be one recorded variable. According to the distribution of this data, the level of variance in ball orientation could be identified and adopted by the machine to replicate the level of variance seen in human cricket bowling. Once the ball has been manipulated it is then linearly translated between the drive wheels of the bowling machine and output down the pitch.

7.3: Conclusions:

The work outlined in this chapter has illustrated and evaluated a method of identifying and manipulating a seamed cricket ball into a known orientation. Using the ball orientation data obtained from player analysis (see Chapter 3) integration of the orientation system into the novel bowling machine will enable manipulation of balls into realistic orientations for each delivery type selected prior to being input into the machine drive wheels.

The initial testing of a tactile method for determining the orientation of a cricket ball seam has produced promising results. Further work is necessary to evaluate fully the limitations of the method (i.e. gauge download speed, accuracy at angles approaching horizontal) and to reduce the time taken to identify the seam position. However the 83% success rate of the final testing session demonstrates a high level of success, especially when considering the other 17 trials positioned the displacement gauge probe on the seam of the ball representing a 4.5% error at most (seam width ≈ 9% ball circumference).

The tactile sensing method results in the manipulation of the ball into a known orientation from an unknown orientation. Once the ball is in this known orientation it is possible to translate it into a desired orientation for each delivery type selected. Further work should include the development of a database of delivery variables from which orientation at release will provide these desired orientations. A combination of translations about the X, Y and Z axes from the known orientation of the ball will present the ball in the desired orientation prior to being linearly translated between the machine drive wheels.

8: Conclusions, Discussion and Continuation of Research

8.1: Research Review

The main research questions that have been addressed within this thesis are associated with four primary objectives (see section 1.2). These were:

(1): The identification of a set of performance criteria essential for a cricket training system, with particular emphasis upon requirement for a novel bowling machine.
(2): The development of elite training programmes.
(3): The design, manufacture and testing of a novel cricket bowling machine.
(4): The identification of further system requirements which are desirable within a cricket training environment.

The first research objective has been fulfilled through the measurement of ball flight characteristics of deliveries released by elite cricketers. A review of existing literature defined the commonly seen delivery variations and these were analysed using high-speed video data captured at the National Cricket Centre, Loughborough University. The measurements obtained from this testing resulted in a detailed range of ball flight characteristics identified for each of the delivery variations. In addition, elite performance during match play was analysed in Chapter 4, where HawkEye, expert commentary and delivery classifications identified from Feedback Cricket performance analysis software were used to evaluate the performance of two of the world's leading bowlers. The ball flight characteristics measured by HawkEye have also been used in the development of the bowling machine performance criteria.

Elite match play analysis conducted using HawkEye ball tracking data has led to the development of a range of ball flight characteristics for each of the delivery types released by the two international bowlers focussed upon. These data can be used for the development of elite training programmes allowing batsmen to face deliveries that are representative of those released by a chosen bowler. The likelihood of facing each delivery type has been calculated based upon the number of each type bowled in a match scenario. The range of ball flight characteristics for each delivery variation has been developed and this forms the working range a bowling machine should operate within when replicating performance of the chosen bowler.

The development of the bowling machine performance criteria has formed the basis for the evaluation of results from the novel bowling machine design validation testing. The identification of these criteria has led to the accomplishment of the third objective, which was to design, develop and test a novel bowling machine design. An analysis of a first generation prototype machine was undertaken where the design and the performance of the machine was reviewed. The first generation design incorporated two counter rotating wheels to drive the ball with a rotating barrel attachment that imparted rifle spin onto the ball. The performance of the machine was examined with respect to its ability to impart spin and speed onto the ball and its pitching consistency. The review concluded that the machine had performed to a level in excess of current player abilities for imparting spin and speed however the design of the machine meant that manual alterations to the spin attachment were required to bowl both pace and spin deliveries and the health and safety of the machine operator was compromised by the large rotating mass of the spin attachment.

A novel cricket bowling machine design was developed incorporating smaller drive wheels powered by single phase motors and a spin head design featuring three rotating rollers inset into a stationary central barrel. Testing of the machine was carried out in the Sports Technology laboratory, firstly outputting balls into a safety enclosure and then a cricket pitch sized enclosure where measurements were taken to quantify the launch characteristics and pitching consistency of balls output. The spin head underwent a series of four design iterations throughout the research and at each stage the capability of the machine to impart speed and spin onto to the cricket ball was evaluated. The prototype design is able to launch correctly oriented cricket balls at speeds and spin rates in excess of current player abilities in a controllable manner. The pitching length capability of deliveries output by the bowling machine is still not as consistent as competitor machines.

The final objective within the research question was to identify additional requirements a cricket training environment must fulfil. In response to this, two case studies have been conducted. The first focuses upon the differences in a batsman's movements when facing a bowling machine and a human bowler. The second case study charts the progress of a method of cricket ball seam detection using a tactile method.

The first case study demonstrated the need for future research to incorporate a representation of a bowler to provide spatial and temporal information about oncoming deliveries. Although limited in number, the data presented in Chapter 6 provided evidence to suggest that training with currently available bowling machines could lead to batsmen developing mistimed technique emanating from inappropriate cues. When facing the bowling machine, the batsman lifted his bat significantly earlier than when facing the human bowler. This resulted in his bat "hanging" at the mid point of his backswing awaiting the ball to be output. Conversely, the batsman lifted his front foot significantly later against the bowling machine than against the human bowler. His foot did not move until the ball had been output from the bowling machine, suggesting that there was no ball length information available to the batsman prior to the ball being output from the bowling machine.

The second case study described the development of a tactile method of determining the position of the seam on a randomly oriented cricket ball. An ultimately unsuccessful optical method of determining the position of the seam was also reviewed in Chapter 7. However, the tactile method produced positive results and it was pursued. The method was developed such that a ball in a random orientation could be manipulated into a known orientation prior to being inserted into the drive wheels of the bowling machine. Using a digital displacement gauge to track around the equator of a ball it was possible to identify the seam and on 83% of tests, the centre seam, even when the seam was tilted from an upright position.

The research has been disseminated within academic circles through the attendance of two international conferences. Papers entitled "High Speed Video Analysis of a Leg Spin Cricket Bowler" and "Cricket Batting Stroke Timing of a Cricket Batsman When Facing a Bowler and a Bowling Machine" have been presented at the Asia Pacific Congress on Sports Technology in Singapore, 2007 and ISEA Engineering of Sport 7 Conference, Biarritz, 2008 respectively.

8.2: Research Achievements

The research has contributed to the body of knowledge in the field of Sports Technology in a number of ways. A quantitative evaluation of the common bowling delivery variations has been carried out. In addition, an analysis of elite human performance during match play has added to the development of performance criteria necessary for a bowling machine to meet if it is to replicate elite human performance. It is believed that the orthogonal high-speed video camera setup used to analyse the ball flight characteristics and release positions of elite human deliveries has not been used before for the analysis of human performance and could be transferred to a number of disciplines (e.g. baseball, tennis, basketball and athletics throwing events)

The prototype bowling machine has been developed to produce human realistic deliveries using real cricket balls released in a known orientation. The design of the machine could be transferred to launch balls for other sports such as baseball and tennis where spin and speed imparted onto the ball are integral elements of the game. The ability of the second generation spin head to impart spin in a known and controlled orientation, particularly rifle spin is fundamental to the recreation of elite spin bowling. The level of spin imparted (40 rps) and forward velocity (105 mph) exceed the current ability of elite players meaning that the operating range when recreating human deliveries will not demand the machine to perform at maximum capability. It does however mean that when training against spin deliveries on artificial surfaces which are perceived to induce less deviation than grass wickets, a greater level of spin can be imparted to deviate the ball an amount representative of that seen in matches.

The research presented in this thesis has continued the development of a novel cricket training system, building upon the work carried out by Laura Justham (2007) with a focus upon the measurement of elite human performance and the design of a bowling machine capable of outputting deliveries with the measured ball flight characteristics. The research has formed a platform for the future development of a next generation training system providing batsmen with a number of key stimuli present in a match scenario. Such a training system has the potential to revolutionise the way in which players train and coaches teach.

Weaknesses of the research carried out is that the current form of the bowling machine: (1) Is too inconsistent in its pitching length and (2) (strongly influenced by the previous weakness) has not been extensively evaluated by batsmen. The only form of machine evaluation has been against the performance criteria established from the player testing and elite match analysis. The machine can produce deliveries with ball flight characteristics that accurately represent (and exceed) human capabilities, however batsmen who face the machine may not perceive it to be accurate. It is therefore important, with the continuation of the research, that player testing and evaluation is carried out in order that a training system fully meets the requirements of players and coaches.

8.3: Continuation of Research

The research is being continued at Loughborough University through the development of the second generation spin head and the automated ball orientation mechanism.

The novel bowling machine design has consistently produced deliveries imparted with higher levels of spin and speed than are seen from elite human performers. However, the pitching length consistency of the machine was not as repeatable as desired. The continuation of the research should first establish the reason(s) for this. Further testing and analysis of the interaction between the ball and the rollers within the spin head is required and an evaluation of the level of interaction's effect on the pitching length of each delivery.

Once the effect of numerous ball/roller contacts has been evaluated, an automated ball feeder (based upon the results detailed in Chapter 7) could be used to control the orientation and timing of ball input between the drive wheels. By synchronising the point of ball input with the position of the rollers within the spin head it is anticipated that it will be possible to control the point of ball/roller impact. Only when a consistent level of this vital interaction is achieved it will be possible to evaluate fully the performance of the second generation spin head and the consistency of deliveries output.

An automated ball feeding unit must input the ball between the drive wheels in the correct orientation for each delivery type selected. A method to determine the position of the seam on a cricket ball has been developed in chapter 7. This theory could be integrated into an automatic feeding unit that acquires a randomly oriented ball, analyses the ball's orientation and manipulates the ball in order that it is inserted between the drive wheels correctly.

The results of the case study presented in Chapter 6 provide further evidence that a bowler representation is required if a training system is to provide batsmen with a realistic environment in which to train. The differences in batting technique observed confirm that visual information is critical to a batsman's judgement of an oncoming delivery and that the use of current bowling machines could lead to deficiencies in technique developing. Further research should look to develop a visualisation screen positioned at the front of a bowling machine as seen in ProBatter (see section 2.6). The visualisation screen and the hole through which the ball was fired would need to move with the bowling machine as deliveries are released from a range of positions (see Chapter 3). A data bank of videos would be necessary to represent each of the delivery variations and the disparity seen in human technique when releasing each of these variations. Additionally, the videos would need to be synchronised with the bowling machine such that deliveries were output at the corresponding stage of the bowling action. Integration of a ball tracking system such as HawkEye could also be developed to determine the trajectory of the ball post impact with the bat providing feedback on the shot played and the position of the ball within a "virtual pitch." A truly virtual cricket training environment would provide the batsman with visual information concerning the position of "fielders" in addition to the bowler and offer the opportunity to "pick the gaps" in the field when playing shots. Integration of a post impact ball tracking system would allow feedback to be provided measuring players' run scoring success.

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Appendix A:

		1	2	3	4	5	6	7	8	9	10
Bowler	Delivery Type	Release Position X	Release Position Y	Release Position Z	Speed	Spin Rate	Ball Orientation at Release	Predominant Spin Direction	Launch Angle	Pitching Length	Pitching Width
		(metres wide of centre stump)	(metres from bowler's stumps)	(metres from floor)	(mph)	(rps)	(degrees from normal)	(degrees normal to spin axis)	(degrees from horizontal)	(metres from bowler's stumps)	(metres wide of centre stump)
Bowler 1	Leg spin	-0.78344	1.2236	2.07776	41.5	26.01	-30	-32	5.54	16.1735	-0.2333
Right Arm	Leg spin	-0.864	1.18864	2.08032	43.98	26.32	-41	-30	7.25	17.32	-0.30645
	Wrong'un	-0.85336	1.15216	2.01632	40.36	31.25	-39	31	4.16	14.41012	-0.2165785
	Slider	-0.61928	1.12328	2.0624	40.27	19.32	-31	-7	6.34	15.75	-0.2564
	Flipper	-0.8184	1.18408	2.02656	46.47	25	0	-175	1.81	18.32	-0.1874915
Bowler 2	Off Break	-1.0084	1.0944	2.17248	43.47	29.67	64	64	2.91	15.59215	-0.3873
Right Arm	Off Break	-1.0768	0.96368	2.17504	42.08	25.95	58	74	4.04	17.09365	-0.57595
	Off Break	-1.17104	0.73568	2.16992	41.41	29.18	59	51	5.61	17.1129	-0.6568
Bowler 3											
Right Arm	Off Break	-0.64968	1.2	2.25184	40.95	32.33	-36	40	-1.85	15.34625	-0.5687
	Off Break	-0.7196	1.17	2.28128	45.23	36.8	-37	41	-0.5	14.52015	-0.2759107
	Off Break	-0.95672	1.09	2.25824	42.52	34.86	-26	31	5.12	17.22	-0.75305
Bowler 4											
Right Arm	Off Break	-0.522	0.89528	2.21088	39.82	25.84	48	41	5.54	15.76925	-0.50665
	Off Break	-0.60712	0.86792	2.1968	40.22	27.65	53	48	5.79	15.78465	-0.8339
	Off Break	-0.45968	1.0488	2.20704	40.39	26.19	52	45	6.7	16.3198	-0.27565
Bowler 5											
Right Arm	Off Break	-1.5708	1.25704	2.376	42.1	23.99	75	26	7.13	17.136	-0.8647
	Off Break	-1.70304	1.1248	2.33632	42.89	19.12	85	36	3.17	16.8203	-0.9186
	Off Break	-1.952	1.2874	2.31712	41.09	20.83	43	42	4.79	16.89345	-0.7415
Bowler 6											
Left Arm	Orthodox	-0.56304	1.18864	2.28128	43.31	25.19	-44	-31	3.61	15.90015	-0.09085
	Orthodox	-0.5904	1.19016	2.24672	40.73	24.47	-42	-12	1.21	14.69235	-0.3508217
	Orthodox	-0.74848	1.1476	2.24928	43.8	24.66	-41	-19	2.77	15.83085	-0.1255
Bowler 7											
Left Arm	Orthodox	-0.8032	0.81776	2.19552	45.75	28.29	-40	-40	1.66	14.82882	-0.4318684
	Orthodox	-0.8792	0.99408	2.184	42.45	27.6	-45	-45	-0.89	14.23566	-0.4431889
	Orthodox	-0.88832	0.86944	2.18784	42.43	28.56	-50	-45	4.74	16.60085	-0.32583
Bowler 8											
Left Arm	Orthodox	-0.68312	0.50312	2.05216	41.35	15.84	-50	-20	8.93	16.75485	-0.4104
	Orthodox	-0.712	0.36176	2.06112	39.1	18.17	-40	-37	9.69	16.3044	-0.5028
	Orthodox	-0.70744	0.608	2.05344	39.86	18.75	-51	-25	6.47	15.7885	-0.57595
	Arm ball	-0.94456	1.24336	2.05984	51.13	17.92	35	-171	-1.49	16.16965	-0.0254
	Leg spin	-0.77128	1.12176	2.05088	41.85	29.81	76	17	1.52	14.60897	-0.6898224

Table A1: Variables measured from the deliveries of spin bowlers.

		1	2	3	4	5	6	7	8	9	10
Bowler	Delivery Type	Release Position X	Release Position Y	Release Position Z	Speed	Spin Rate	Ball Orientation at Release	Predominant Spin Direction	Launch Angle	Pitching Length	Pitching Width
		(metres wide of centre stump)	(metres from bowler's stumps)	(metres from floor)	(mph)	(rps)	(degrees from normal)	(degrees normal to spin axis)	(degrees from horizontal)	(metres from bowler's stumps)	(metres wide of centre stump)
Bowler 9											
Right Arm	Standard	-0.97496	1.102	2.0944	60.13	13.66	-11	179	-6.06	13.82746	0.1118255
	Standard	-1.08136	1.14152	2.08928	64.45	16.94	-21	173	-4.48	15.09415	-0.618593
	Standard	-0.95064	1.03968	2.06752	66.21	10.63	-36	132	-4.98	14.62121	-0.443796
	Standard	-1.01144	1.21752	2.07648	68.11	11.43	-27	155	-2.95	20.12	-0.1143
	Standard	-1.05704	1.0868	2.06112	70.49	18.87	-26	138	-6.26	14.28242	-0.172005
	Standard	-1.0312	1.21904	2.07648	66.61	18.3	-28	139	-4.98	15.08962	-0.410322
Bowler 10											
Right Arm	Standard	-0.81992	1.1628	2.1776	67.2	16.11	-21	175	-8.75	13.7354	-0.855353
	Standard	-0.6968	1.21752	2.18656	67.44	19.17	0	180	-11.71	13.16553	-0.5023
	Standard	-0.71352	1.23272	2.22368	66.83	16.23	-8	177	-6.72	14.56315	-0.38147
Bowler 11											
Right Arm	Standard	-0.5144	1.178	2.0752	73.27	19.07	-1	175	-8.13	14.12852	-0.295892
	Standard	-0.48552	1.08376	2.0368	77.19	20.73	-6	178	-2.61	20.12	0.7483087
	Standard	-0.60864	0.99104	2.08288	73.94	19.62	-8	179	-4.65	16.53925	-0.29875
	Standard	-0.56	1.28288	2.03808	76.8	25.04	0	177	-6.68	14.38688	-0.01137
	Standard	-0.63296	1.26312	2.03168	73.45	17.78	-2	179	-8.43	13.75549	-0.171849
	Standard	-0.53416	1.42272	2.05856	76.35	18.48	0	180	-5.85	15.9733	0.06315
Bowler 12											
Right Arm	Standard	-1.04184	0.84208	2.02656	73.41	17.1	-2	178	-7.13	13.99454	-0.967633
	Standard	-1.07224	1.06096	2.0304	74.1	18.6	-9	163	-5.23	16.1889	-0.93785
	Standard	-0.99928	0.87704	2.056	75.47	10.19	4	180	-5.21	15.90785	-0.8262
	Standard	-0.95216	1.12784	2.00736	74.28	18.89	-1	-178	-6.49	14.60662	-0.760226
	Standard	-1.01448	1.06096	2.01504	77.38	12.05	2	-179	-3.53	18.82	-0.187491
Bowler 13											
Right Arm	Standard	-0.60408	0.95608	2.1392	76.15	8.83	2	179	-7.03	14.51093	-0.253812
	Standard	-0.67856	0.85576	2.13664	77.31	14.56	-2	178	-6.18	14.88914	-0.56948
	Standard	-0.59952	1.13392	2.1392	73.5	15.89	0	177	-6.16	16.1581	-0.43735
	Standard	-0.5752	0.84512	2.13664	75.54	18.05	-1	179	-7.60	14.39702	-0.186199
	Standard	-0.60712	0.9728	2.12896	77.4	12.53	-1	178	-5.64	16.37755	-0.241
	Standard	-0.63904	1.12936	2.10848	76.41	11.04	-3	180	-8.63	13.92629	-0.4343
Bowler 14											
Right Arm	Standard	-0.97523	1.3245	1.99072	71.36	8.91	-3	179	-7.23	14.0273	-0.460674
	Standard	-0.94326	1.5678	1.97152	70.39	10.3	-10	180	-8.21	13.57482	-0.335577
	Standard	-0.932	1.321	1.98688	72.73	11.2	-21	176	-6.05	13.36468	-0.545411
	Standard	-0.96736	1.43488	1.98432	72.25	10.3	-12	-178	-7.28	13.39562	-0.554848
	Standard	-0.92784	1.29808	1.99072	70.01	15.6	-12	-179	-8.00	13.31008	-0.407885
Bowler 15											
Right Arm	Standard	-0.68312	0.54112	2.03168	72.57	21.66	-55	-176	-6.27	14.32501	-0.31925
	Standard	-0.59952	1.48504	2.06368	67.03	10.56	2	-175	-5.55	16.57775	-0.08315
	Standard	-0.55544	1.35432	2.11232	69.07	13.19	10	-175	-4.53	16.28515	-0.38345
Bowler 16											
Right Arm	Standard	-0.52341	1.75236	2.0125	70.67	2	1	180	-17.10	13.4547	-0.141443
	Standard	-0.63208	1.72146	2.1368	71.23	5.63	2	178	-19.20	12.93628	-0.487633
	Standard	-0.499862	1.78965	2.00794	70.12	5.89	9	-175	-16.36	13.50195	-0.01343
Bowler 17											
Right Arm	Standard	-0.32051	1.5869	2.02016	70.58	12.61	5	180	-14.04	12.9591	-0.421185
	Standard	-0.25621	1.6893	2.01888	71.23	8.83	4	180	-10.23	13.07726	-0.351398
	Standard	-0.24232	1.44552	2.12128	68.2	1.82	10	-177	-8.99	13.4393	-0.104255
	Standard	-0.29563	1.44589	2.05344	72.36	7.65	9	-178	-9.21	13.15881	-0.397936
	Standard	-0.28562	1.52361	2.09952	73.1	4.12	1	-179	-9.01	13.38183	-0.397603
Bowler 18											
Left Arm	Standard	1.49264	-0.92632	2.05856	78.39	13.56	-4	180	-5.00	16.6894	-0.29888
	Standard	1.39384	-0.95064	2.02784	78.08	2.22	-3	-177	-6.46	14.88354	-0.290947
	Standard	1.56104	-0.9552	1.99584	74.73	5.91	-2	-176	-12.05	13.17148	-0.111912

Table A2: Variables measured from the deliveries of pace bowlers.

Appendix B:

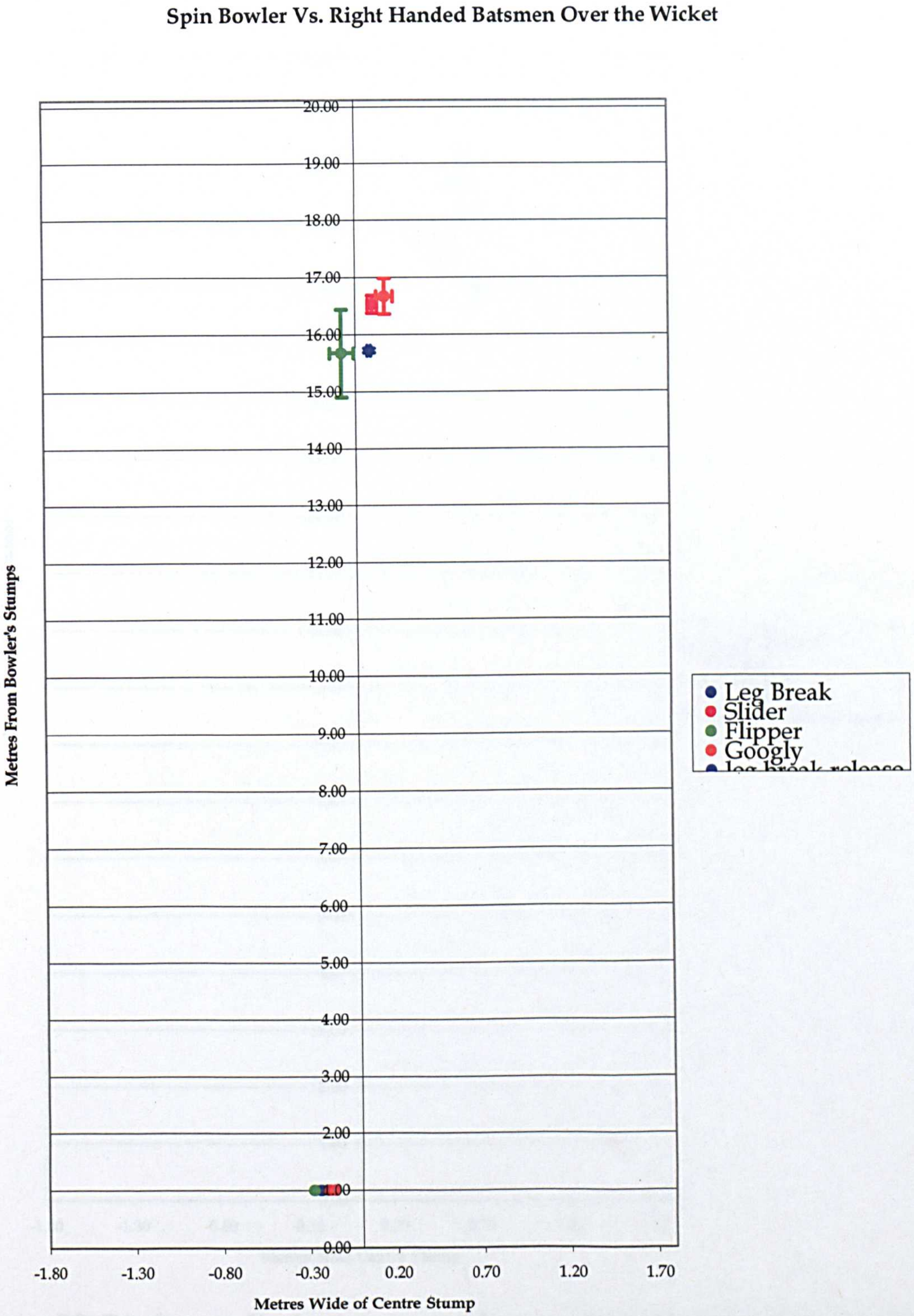

Figure B1: Pitch map displaying mean release and pitching positions for spin deliveries bowled to right handed batsmen from over the wicket. Error bars represent the standard error in the mean.

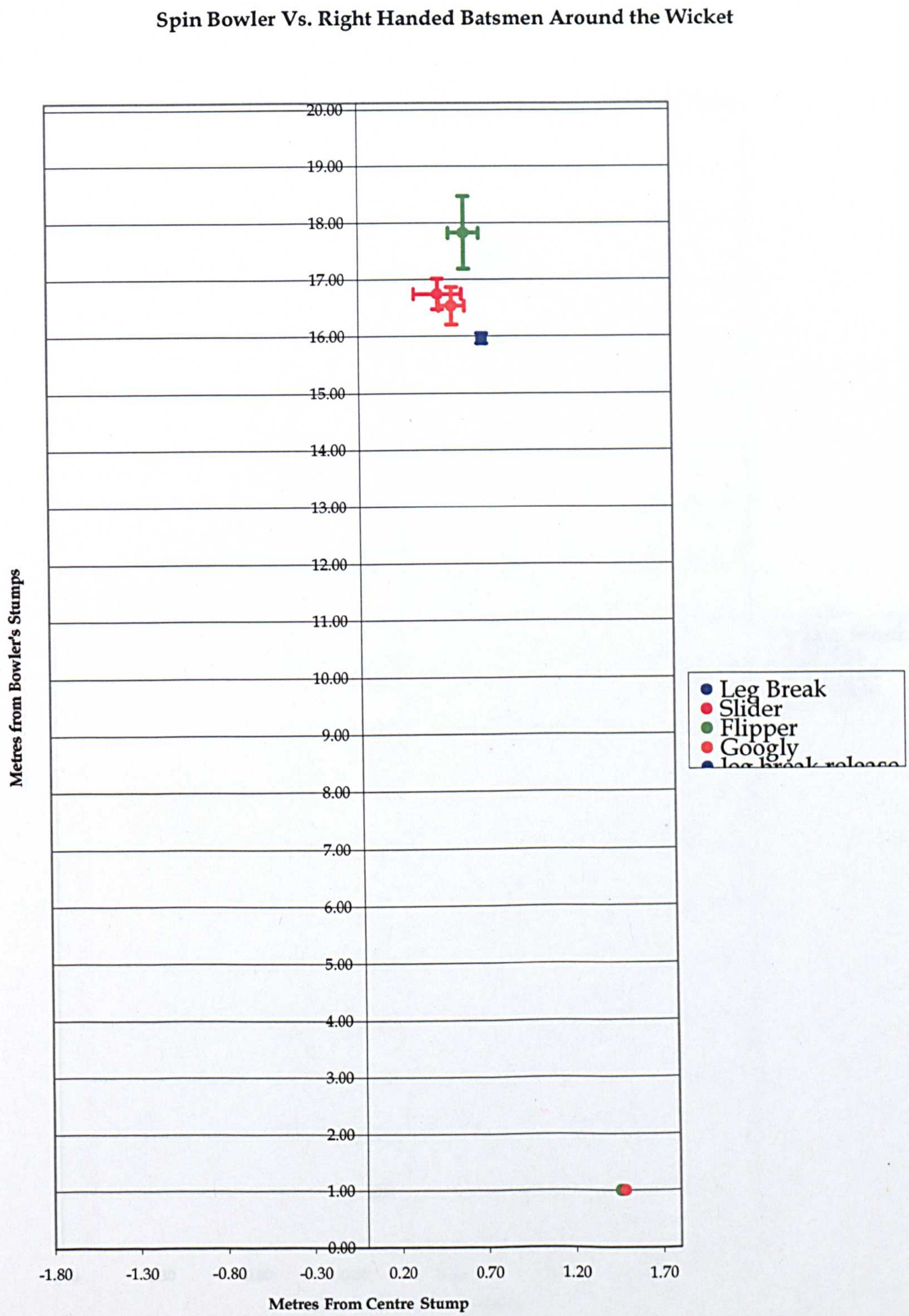

Figure B2: Pitch map displaying mean release and pitching positions for spin deliveries bowled to right handed batsmen from around the wicket. Error bars represent the standard error in the mean.

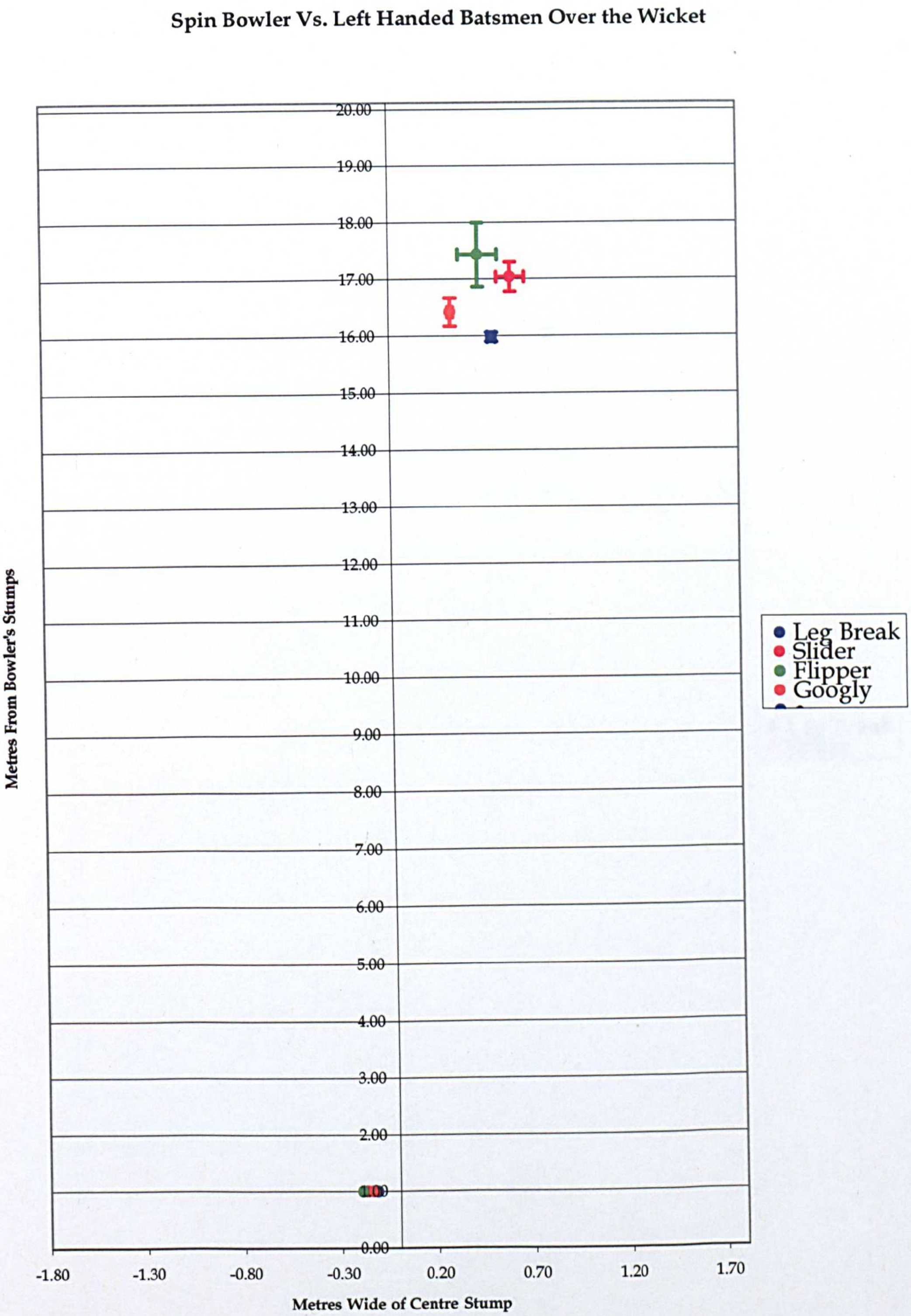

Figure B3: Pitch map displaying mean release and pitching positions for spin deliveries bowled to left handed batsmen from over the wicket. Error bars represent the standard error in the mean.

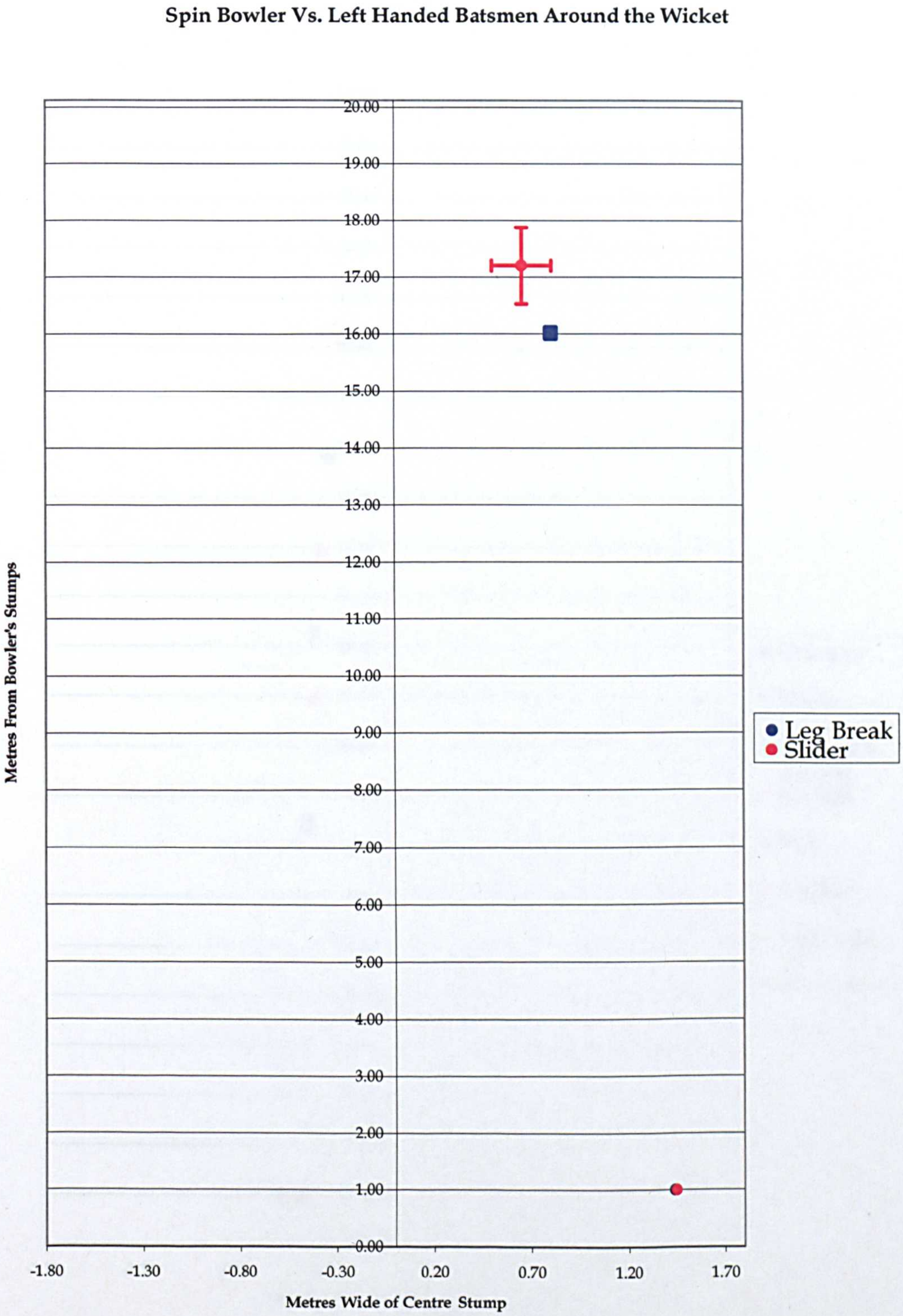

Figure B4: Pitch map displaying mean release and pitching positions for spin deliveries bowled to left handed batsmen from around the wicket. Error bars represent the standard error in the mean.

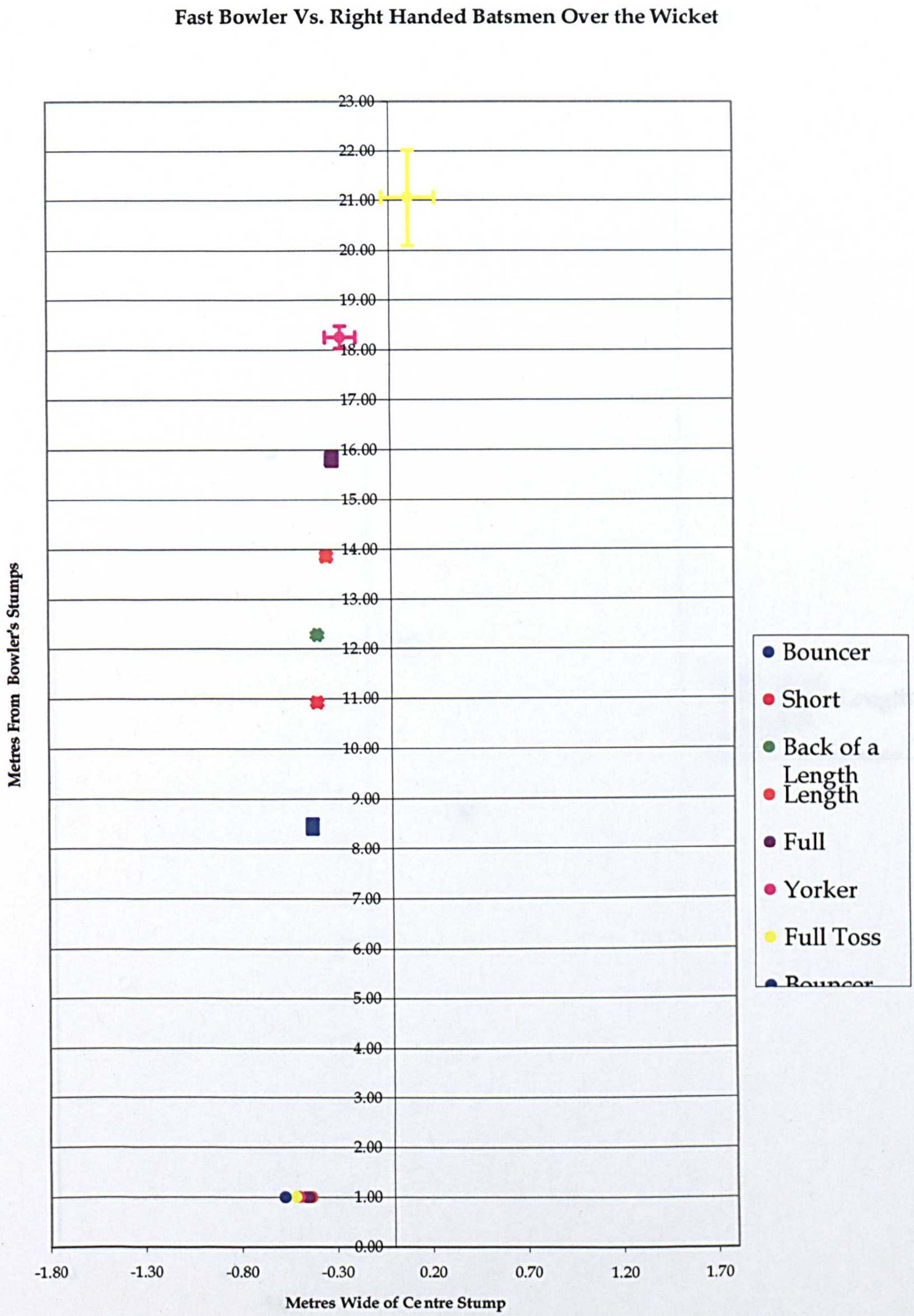

Figure B5: Pitch map displaying mean release and pitching positions for pace deliveries bowled to right handed batsmen from over the wicket. Error bars represent the standard error in the mean.

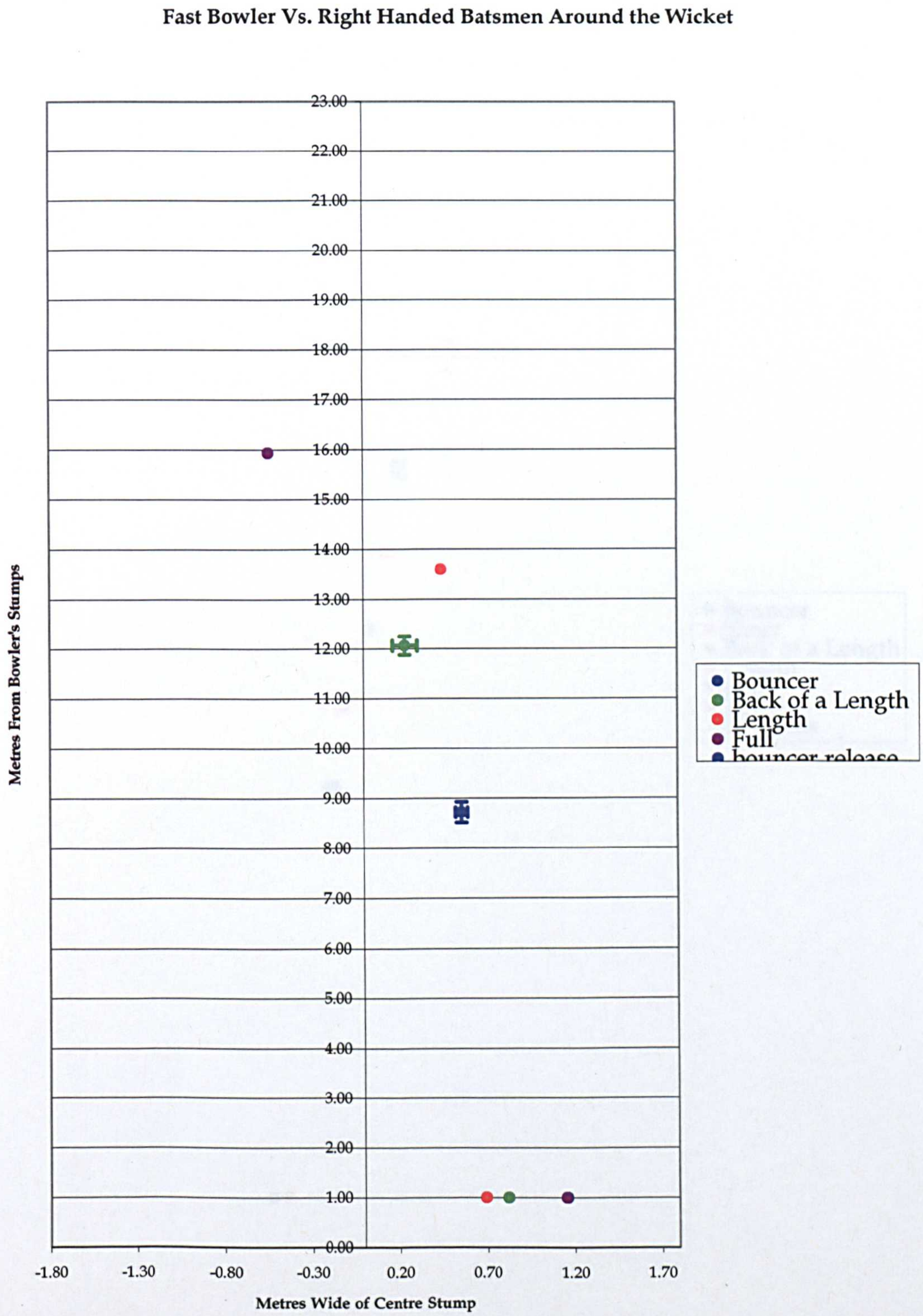

Figure B6: Pitch map displaying mean release and pitching positions for pace deliveries bowled to right handed batsmen from around the wicket. Error bars represent the standard error in the mean.

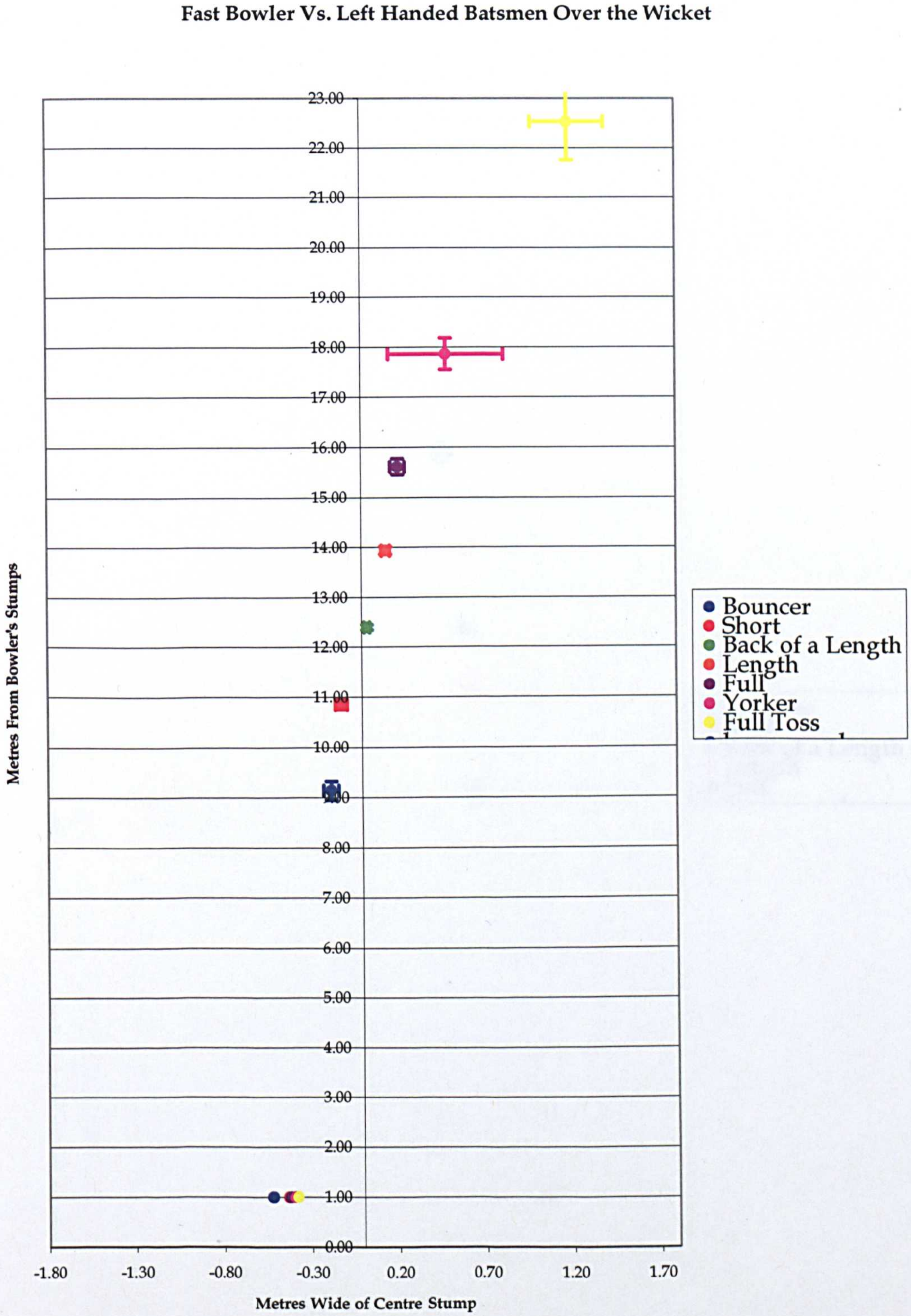

Figure B7: Pitch map displaying mean release and pitching positions for pace deliveries bowled to left handed batsmen from over the wicket. Error bars represent the standard error in the mean.

Figure B8: Pitch map displaying mean release and pitching positions for pace deliveries bowled to left handed batsmen from around the wicket. Error bars represent the standard error in the mean.