A biomechanical analysis of fast bowling variations

PUBLISHER

Loughborough University

REPOSITORY RECORD

Manawadu, Kaushal. 2023. “A Biomechanical Analysis of Fast Bowling Variations”. Loughborough University. https://doi.org/10.26174/thesis.lboro.23566362.v1.

A Biomechanical Analysis of Fast Bowling Variations

by

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A Doctoral Thesis

Submitted in partial fulfilment of the requirements for the award of Doctor of Philosophy at Loughborough University

October 2022

ABSTRACT

A Biomechanical Analysis of Fast Bowling Variations

Kaushal Manawadu, Loughborough University, 2022

The ability for bowlers to successfully bowl different length fast bowling deliveries is an important but challenging task. This study investigated fast bowling pitch length delivery types using a full body three-dimensional kinematic and kinetic analysis. 21 county fast bowlers performed 48 deliveries (12 yorkers, 12 bouncers and 24 stock balls) with an eighteen camera (MX3) Vicon motion analysis system (250 Hz) and a Kistler force plate (1000 Hz) recording each trial. The bowlers were found to be most consistent at bowling bouncers (98% success rate) compared to stock and yorker deliveries (46% and 25% success rate respectively). Repeated measures ANOVA revealed significant differences in ball release angle and ball release height between the three delivery types. Ball – finger 2D orientation angle, wrist angle, 2D orientation of hand segment, thoracic angle and 2D orientation of the thoracic were the main technique parameters which explained from 31% to 89% of the variation in ball release angle and ball release height percentage predictive equations. The thoracic angle and wrist angle time histories (back foot contact to ball release) had periods that were significantly different across the three types of delivery. Furthermore, SPM analysis revealed significant changes ($p = 0.03$) in wrist moments for bouncers compared with yorkers and stock balls between front foot contact and ball release. In conclusion, this study provides an understanding of the technique parameters most associated with different length deliveries in cricket fast bowling. These results provide a foundation for coaching and future research, in particularly investigating the kinematic and kinetic factors linked with different length fast bowling deliveries and different action classifications.

PUBLICATIONS

Conference presentation and published abstract

Manawadu, K., Felton, P., Hiley, M. and King, M., 2022. A comparison of pitch length variations and the ability to control length in cricket fast bowling. ISBS Proceedings Archive, 40(1), p.411.

ACKNOWLEDGEMENTS

I would like to thank Loughborough University for this wonderful opportunity to do this study with the highest possible technology and equipment. Prof. Mark king, who is my main supervisor has helped me from the skype interview which I had back in Sri Lanka until the end of the studies. In addition, Dr Paul Felton, Dr Michael Hiley and Dr Stuart Mcerlain-Naylor's whose input have been invaluable, challenged me to think differently and finish the study on time.

I would also like to thank the team members of the Sports Biomechanics Group at Loughborough, namely Dr Pete Alway and Matt Lamb for their help in data collection sessions during the COVID-19 pandemic times. Special thanks to Yash Deshpande for helping me with his MATLAB expertise during the study.

Finally, I would like to thank my father mother, sister, Naduni, all the other friends and Dr (Mrs.) Sashie Weerasinghe who is head of the Sports Science Department at the University of Sri Jayewardenepura for their support and encouragement.

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CHAPTER 1

INTRODUCTION

Cricket is globally recognised as the second most popular sport in the world and originated in England with batting, bowling, and fielding the three main skills in cricket. Among them fast bowling is a skill which players all over the world aspire to master using a variety of strategies to deliver the ball faster than other bowlers with the idea of beating the batter primarily with speed. More recently fast bowlers have become more proficient at using different variations to deceive the batsmen. This chapter provides an overview of the study and aims along with an outline of each chapter.

1.1 Area of study

In cricket, the topic of fast bowling has been the one where most of the academic studies have been carried out. Furthermore, fast bowling biomechanics has been considered for investigation with two main purposes. Firstly, to identify injury patterns or reduce injury risks due to the high explosive forces acting on the joints or unhealthy techniques. Secondly to identify the key performance characteristics to bowl fast which reduces the batter's decision making and stroke execution time.

A large number of performance characteristics have been considered in finding the most effective factors in producing the fastest delivery for different types of bowlers. Each bowler has his/her unique way of beating the batsmen, but when it comes to fast bowling, bowling speed has been the most decisive factor for many years in selection criteria of players. The speed of the ball is one of the major characteristics in fast bowling where many things should be put together such as proper joint angles at ball release and higher loading rates from front foot contact to ball release (Najdan et al., n.d.; Portus et al., 2004; Worthington, 2010).

The game of cricket has developed and changed vastly since the beginning of the sport (Stretch et al., 2000; Noorbhai, 2015a). As per the requirement of the present-day competitions which are shorter in time and require higher strike rates, batsmen tend to attempt predetermined shots when they are familiar with the line and length of the delivery.

From a bowler’s perspective, fast bowling speed is not the only dominant performance factor due to the modern-day arrangements of the game and development of training infrastructures where the batters can use a bowling machine to feed up to 100 mph during the practice sessions and recreate the game situation. Therefore, using a predetermined bowling variation can also outthink the batters and put the bowler on top.

Most of studies have been conducted with the idea of finding the main kinematic and kinetic factors, by dividing the fast-bowling action into a sequence of key phases (Davis and Blanksby, 1976b; Elliott et al., 1986; Burden and Bartlett, 1990a; Portus et al., 2004) (Figure 1.1). At the start of the fast-bowling skill, bowlers use an approach run to gather momentum and some of the studies have mainly considered the contribution of run-up length or run-up speed on ball release speeds (Davis and Blanksby, 1976a; Elliott et al., 1986).

The predelivery stride connects the run up to the delivery stride with a stride or a jump. Very few studies have been published on the length of the pre delivery stride but David and Blanksby (1976b) found that predelivery stride is 0.42 m longer for faster bowlers than the other fast bowlers. Depending on the action, different techniques will be used in the pre delivery stride whether to leap forward or jump higher (Andrews, 1984).

The back foot contact phase (Figure 1.1B), the next key instance in the fast-bowling sequence has received more attention with investigations on different aspects of back leg techniques (Elliott et al., 1986; Burden and Bartlett, 1990b; Portus et al., 2004) while some studies have classified the bowling action depending on the orientation of the hip- shoulder alignment (Glazier, 2000; Worthington, 2010).

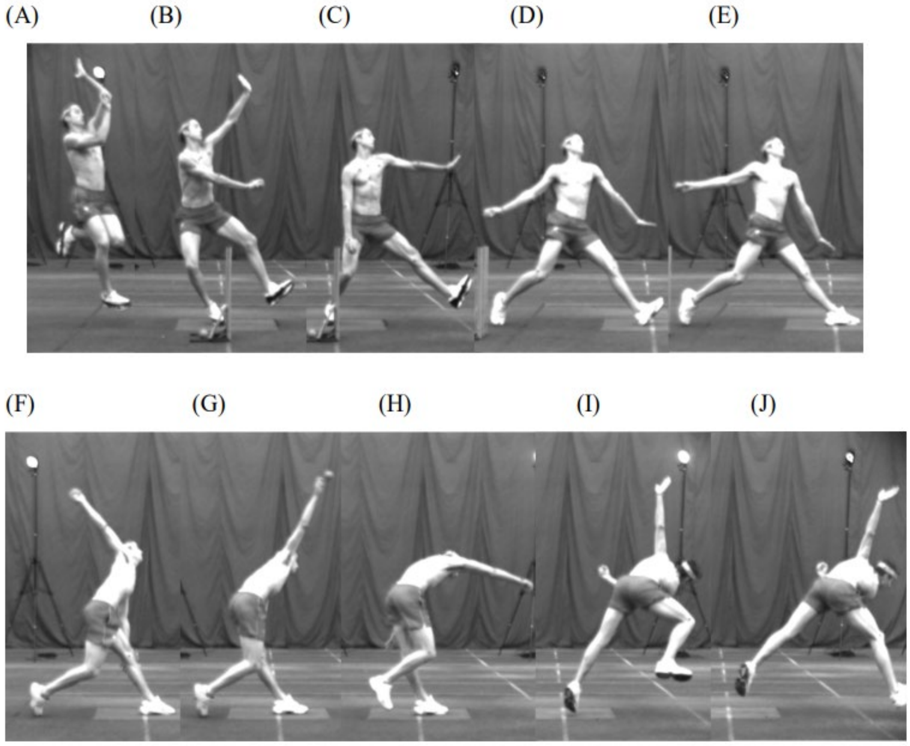


Figure 1.1: The fast-bowling sequence (taken from Worthington, 2010).

The kinematics bowlers create from back foot contact to ball release can vary leading to individualised technical characteristics. For example, the position of the bowling arm relative to the body at ball release has been studied for more effective outcomes (Davis and Blanksby, 1976b; Elliott et al., 1986; Burden and Bartlett, 1989; Foster et al., 1989; Burden, 1990).

Kinetic parameters such as peak loading rates, vertical forces and braking forces have also been reported to be important in classifying and understanding the fast-bowling action (Elliot et al., 1992,1993; Portus et al., 2004; Worthington, 2010). These kinetic parameters were investigated initially to find out any relationships with injury patterns specifically in the lumber vertebral area. Whole body biomechanical loading seems to have no significant difference across different length deliveries in both discreet and continuous analyses (Callaghan et al., 2021) although there are not many studies on bowling variations.

Some studies have identified and quantified the EMG activity in selected muscle groups (Biceps brachii) during fast bowling (Ahamed, 2014). Furthermore, EMG activity in the shoulder and wrist has also been investigated for yorker and bouncer deliveries to find out the differences (Hazari, 2015). Although more limited than ball release speed, some previous research has investigated the variations in ball axis orientation and spin, which lead to movement in the air (‘in swing’ and ‘out swing’ deliveries), and the effect on reducing batting performance (Sarpeshkar et al., 2017; Woolmer et al., 2008).

This study aims to investigate the techniques used between back foot contact and ball release in order to pitch the ball in different predetermined areas.

1.2 Statement of purpose

The main purpose of this study is to understand how bowlers achieve different length deliveries using a three-dimensional kinematics and kinetics analysis for three major bowling delivery types (stock ball, yorker and bouncer).

1.3 Research questions

1. ***How well can senior English county bowlers control the length of a delivery?***

This study will examine how well bowlers can achieve different lengths of delivery. Bowlers will be asked to bowl deliveries of different lengths and a statistical analysis of the data will be used to establish how well bowlers can achieve different lengths of delivery.

Ball release parameters (height, velocity, and angle) and the path of the ball prior to release will be examined to understand how different length deliveries are achieved.

2. ***Which kinematic parameters are more important in producing different length deliveries?***

Previous studies have highlighted technique characteristics associated with increased ball release speed using only stock length deliveries. Variations of length, however, such as yorkers and bouncers, are often used to increase the odds of taking wickets especially in the shorter formats of the game. Despite this, no studies have currently investigated the technique variations associated with changes in pitch length. This question aims to investigate the variation in ball release parameters associated with different ball lengths and the kinematics of the fast-bowling action. This knowledge can be useful for the technical development of future fast bowlers and the coaches.

3. ***What kinetic parameters (forces and torques) are more important in bowling different length deliveries?***

The kinetics of the fast-bowling action have been studied for stock length deliveries, but there is also limited understanding of the variation of kinetic parameters associated with different length deliveries. Previously, most studies have investigated the peak loading rates and vertical ground reaction force at crucial points of fast bowling action normalised to a bowler's bodyweight. Callaghan et al. (2021) found that the whole-body biomechanical loading seemed to have no significant difference across different length deliveries in a two-over spell of fast bowling. This question will consider how kinetic variables change with relation to different length deliveries,

1.4 Chapter organisation

Chapter 1 introduction to the study with the objectives and research questions stated. This chapter also explains the importance and uniqueness of the study.

Chapter 2 describes the literature which underpins the study and explains all the cricket fast bowling specific terminology. The phases of a fast-bowling sequence and the classifications according to different studies will be explained in this chapter. Although fast bowling pitch length delivery type studies are scarce, the results and findings of previous studies on fast bowling speed in reference to the parameters which are expected to investigate in this study will be explained. Findings of similar studies (investigating different variations) in other sports also will be considered.

Chapter 3 provides details on the equipment used for the data collections and the data collection environment along with the procedures. A brief explanation will be given on each step from data collection to the final discreet and continuous data output.

Chapter 4 explains all the 3D kinematic and 2D DLT analysis procedures along with inverse dynamics analysis. The determination of each technique parameter is explained, and the segmental analysis details provided.

Chapter 5 – 8 are written in the form of journal papers and address the main research questions. **Chapter 5** mainly covers the first research question on how well the bowlers can control their length and how successful they have been. The differences among the group are discussed and the expected and actual differences in pitch lengths explained. **Chapter 6** considers the kinematic technique parameter differences among the groups at the instance of ball release. **Chapter 7** considers the joint angle changes from back foot contact to the ball release in a continuous analysis. **Chapter 8** uses an inverse dynamics analysis to calculate the joint moments for the pitch length groups with both a discreet and continuous analysis.

Chapter 9 This chapter brings the whole study together, addresses the research questions, considers the limitations of the study and looks to potential future studies.

CHAPTER 2

LITERATURE REVIEW

This chapter provides a review of cricket fast bowling research and its relevance to the current study.

The fast-bowling action is identified as a collection of activities. Studies often divide the fast-bowling activity into a sequence of events and study each of them individually (Figure 2.1). Run up, back foot contact, front foot contact and ball release have all been chosen as key activities or instances where technique parameters have been investigated.

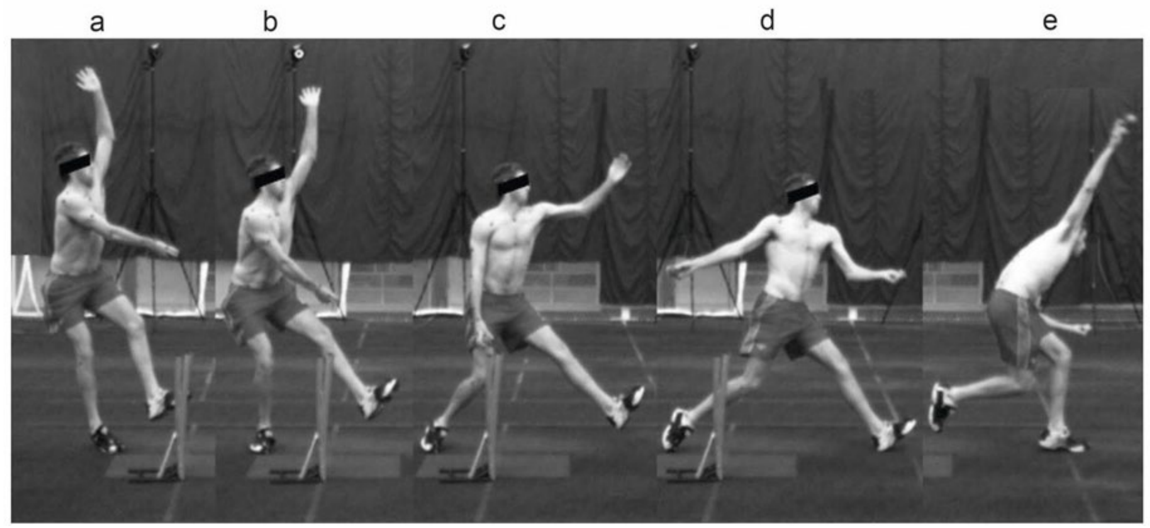


Figure 2.1: The sequence of fast bowling. (The delivery stride of fast bowling: (a) back foot contact (b) back foot flat (c) minimum shoulder angle (d) front foot contact; (e) Front foot flat and ball release (taken from Ranson et al., 2008a).

2.1 Run up

The run up is the first phase of the fast-bowling action. Bowlers choose their own run up length according to their run up speed and rhythm. The run up should be smooth, rhythmic, and long enough to add the maximum impact for the delivery (Tyson, 1976).

Many studies have mentioned the importance of the run up and have discussed different aspects (Elliot and Foster, 1989; Davis and Blanksby, 1976a). The run up doesn't have a proper explanation on how to do it. Bowlers have been observed to use a number of different variations to ensure each of them feels confident at their individual optimal speeds at the end of the run up to deliver the ball. As running technique varies, there is no optimal length for fast bowlers run up (Bartlett et al.,1996). Although run up technique is different from bowler to bowler, they all gather momentum by gradually increasing their speed before leaping into the air for the pre-delivery stride and landing at the point of back foot contact. Despite no agreement on run-up length or speed Elliott and Foster (1989) have suggested a rhythmic balanced run up between 15 – 30 m. While Davis and Blanksby (1976a), identified that a 14-pace run up was sufficient to produce 37 ms^{-1} ball release speed (equivalent to 133 kmph/ 83 mph). In another study, Davis and Blanksby (1976b) found faster bowlers utilised a 2.14 m longer run up than the slower fast bowlers. Although there was a length difference, no link was found between length verse run up speed.

Blazevich (2010) conducted a study on the forces and the inertia acting on the ball and how to increase them for a faster bowling speed. In this study, the run-up phase was discussed with reference to Newton's Laws of motion. Newton's first law states that 'An object will remain at rest or continue to move with constant velocity as long as the net force equals zero'. This was applied to the run up to explain the importance of the ball not moving until the run up starts. When the bowler starts the run up, the ball inherits the bowler's velocity as it moves with the bowler's body. Increasing the running speed throughout the run up on approach will create higher momentum. The momentum gained can then be transmitted to the ball at the end of the bowling sequence.

Ferdinands (2008) mentioned the importance of controllability, the bowler needs to design the length, speed, and rhythm of their run up as they will be able to control and decelerate their body during pre-delivery stride. Newton's Second Law states that 'The acceleration of an object is proportional to the net force acting on it and inversely proportional to the mass of the object'. The run-up speed needs to be at an appropriate controllable level as it is important to maintain linear momentum during the bowling action to help the summation of forces. (Bartlett, Stockill, Elliott, and Burnett, 1996). Moreover, Newton's Second Law also supports the deceleration process in the run up just before the pre delivery stride. Therefore, each subject will use a different approach in the run up as they have different body parameters (Ranson, 2008).

Newtons Third Law has also been used in explaining the importance of a proper run up and running technique. Newton's Third Law states that 'for every action, there is an equal and opposite reaction. Therefore, optimising the acceleration. This concept can be applied in the cricket run up as well to create maximum acceleration before the pre delivery stride.

The angle of the run-up has also been considered with, some cricketers using a curved run up to help them have a more closed shoulder at the point of back foot contact and achieve a side on action more easily. (Philpott, 1973; Tyson, 1976). Side on bowling actions were exclusively coached to young bowlers at one stage since it was found to be the sole technique in the early times of the game. This might have triggered the adoption of curved run up as explained by Philpott (1973). Also, Elliott and Foster (1984) found out faster run up speeds on front on bowlers than side on bowlers in Australian national players.

Many studies have investigated the effect of run up speed on ball release speed. Brees (1989) experimentally asked the bowlers to bowl using three different run-up speeds to identify the variances in kinematics and accuracy. This study found positive corelations of ball release speed with run up speed, but negative corelations with the accuracy. This reflects what other studies suggested which is to have a controlled approach speed to deliver the ball accurately. Davis and Blanksby (1976) and Elliot et al. (1986) studied and analysed the importance of run up speed for the ball release speed by subtracting the centre of mass speed just before the back foot contact from the final ball release speed. Results showed 15% - 19% of the ball release speed was contributed by the run-up speed. And fast bowlers showed a 15% quicker run up than the medium pace bowlers as well. While Glazier et al. (2000) observed the same strong relationship, Burden (1990) stated a contrasting result of no relationship between ball release speed and run up speed. These results are debatable however as run-up speed was measured at the instance of ball release which is different to most other studies. Worthington (2010) also found a linear relationship between run-up speed and ball release speed and identified this as one of four key characteristics of the faster bowlers within his study. Felton (2014) meanwhile found ball speed began to decrease at higher run up speeds due to the inability to coordinate technique, Stride length has also been identified as an integral part of fast bowling technique and is defined as the distance between the front and back foot during the delivery when both feet are still in contact with the ground. Stride length has been positively associated with run up speed with faster bowlers having longer stride lengths compared to slower fast bowlers (Elliott and Foster, 1989). It has been suggested that a player’s stride length is approximately 75% - 85% of their height (Elliott and Foster, 1989a). Elliot and

Foster (1989), however, warned that too much run-up speed can result in a shorter stride length with an uncontrolled delivery. It was also suggested that the alignment of the run-up should follow the stumps at the batsmen's end, front foot and the back foot in a straight line during the delivery stride (Elliot and Foster, 1989). Supporting this statement Elliott et al. (1986) reported a very small mean displacement of 3.2 cm of the front foot to the offside for a right-hand bowler. Although Elliott et al. (1992) recorded contrasting results of 10.9 cm displacement from the back foot line towards the leg side of the batsmen at the point of front foot contact. Since the current study is mainly concentrating on the pitch length, there was no previous studies done in order to find out whether there are any significance differences in run up speed with the differences in pitch length.

2.2 Pre delivery stride

The pre-delivery stride is a very crucial skill which should be perfected in the bowling sequence. At the end of the run up the bowler leaps into the air and organises themselves and prepares for the landing of the back foot and the delivery stride. Pre delivery stride starts when the right foot for a left-hand bowler or the left foot for a right-hand bowler contacts the ground just before the landing of the back foot for the delivery stride (Bartlett et al., 1996).

The pre delivery side is also important in organising the body for shoulder hip separation (Elliott and Foster, 1989a). It is important for s bowlers to gain a position at the pre delivery step for a rapid torso twist or a shoulder counter rotation (Penrose et al.,1976). Previous studies have suggested that 57-58% coaches feel that the pre-delivery stride is important to the speed of the delivery (Davis and Blanksby, 1976a). Bartlett (1996) reviewed this and stated that the leap into the air is needed to gather the maximum linear velocity of the bowler. Although a leap is used to maintain the momentum just before the delivery stride, the direction of the leap plays a major role in achieving the targeted result which is to gain momentum and deliver it to the ball. If the leap direction is upwards due to the impact of centre of mass the momentum will be downwards. Therefore, a flatter and a longer jump towards the running direction allows the bowler to maintain momentum in the needed direction (Magias, 2015). This has been demonstrated by elite fast bowlers who have been successful in producing ball speeds over 90 mph without leaping 'high' into the air during the pre-delivery stride.

Davis and Blanksby (1976) found that the fastest bowlers in their study also tended to adjust and increase their pre-delivery stride length by 22% (0.42 m) compared to their normal stride length. This allowed bowlers to reduce speed and gain maximum control and adopt the correct alignment before the final thrust. This change in stride length was only 0.05 m for slower fast bowlers in this study. However, the same study suggested that this deceleration may not be applicable to mall bowlers as some do not need extra time to twist the shoulders. Andrew (1984) also stated that these different requirements for different bowlers may impact the height of the leap, or the bound even though not much statistical verification was included in the study.

Investigating the nature of different bowlers' techniques has led to the creation of action classification systems based on the orientation of the human body at different stages of the delivery stride.

2.3 Fast bowling action classification

Cricket fast bowling actions have been classified using different factors from time to time. The most used factor is the alignment of the body at back foot contact and the changes of the body from back foot contact to the ball release.

The first action classification began with reference to the back foot contact orientation. Earlier in 1976, the Marylebone Cricket Club (MCC) coaching book suggested the orientation of the back foot at the point of back foot contact as a good indicator in deciding the action. This classification suggested that the back foot should land parallel to the popping crease with the hips and shoulders aligning straight down the wicket making 180° with the bowling direction for a perfect side on action. Although this method was initiated, researchers found it difficult to categorise the bowlers into this. Davis and Blanksby (1976) found only 33.3% bowlers fit this classification. While Elliot et al. (1992) could only classify 15% of their bowlers.

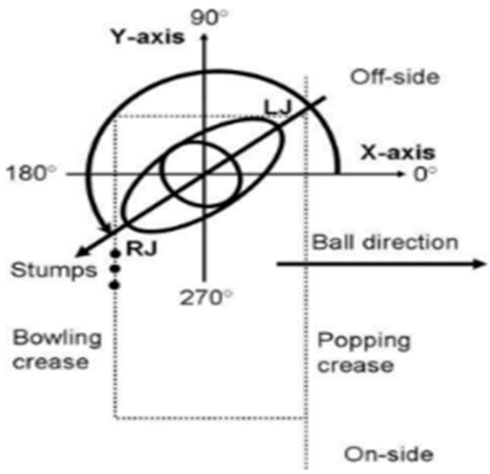


Figure 2.2: Shoulder alignment angles measurement used for bowling classifications at the back foot contact (taken from Ferdinands et al., 2010).

A second action classification system was designed by Elliot and Foster (1984) to describe the bowling technique when investigating the biomechanical differences which may affect fast bowling performance. An update by Foster et al. (1989), was the first to categorise bowlers by including the shoulder orientation angle (Figure 2.2). In this classification, a shoulder orientation angle greater than 200º at the point of back foot contact was classed as 'front on' and a shoulder orientation angle smaller than 190º at back foot contact was classed as 'side on'. In addition, if a bowler the subsequently counter-rotates their trunk from a side on position to a more front on position (more than 40º), they were classed as 'mixed'. This was further adapted by Portus et al. (2004) who introduced using the pelvis shoulder separation angle (Figure 2.3), as well as the alignment of the shoulders at the back foot contact and the amount of shoulder counter rotation (Table 2.1; Figures 2.3 and 2.4). Portus et al.'s (2004) method has been adopted and analysed by Ranson et al. (2008), Worthington (2010) and Thiyagarajan (2015). The findings have been inconsistent due to the method, however, as different anatomical locations have been selected to define the shoulder and pelvis segments, and different instants have been used to define back foot contact e.g. first contact vs foot flat (Ranson et al., 2008).

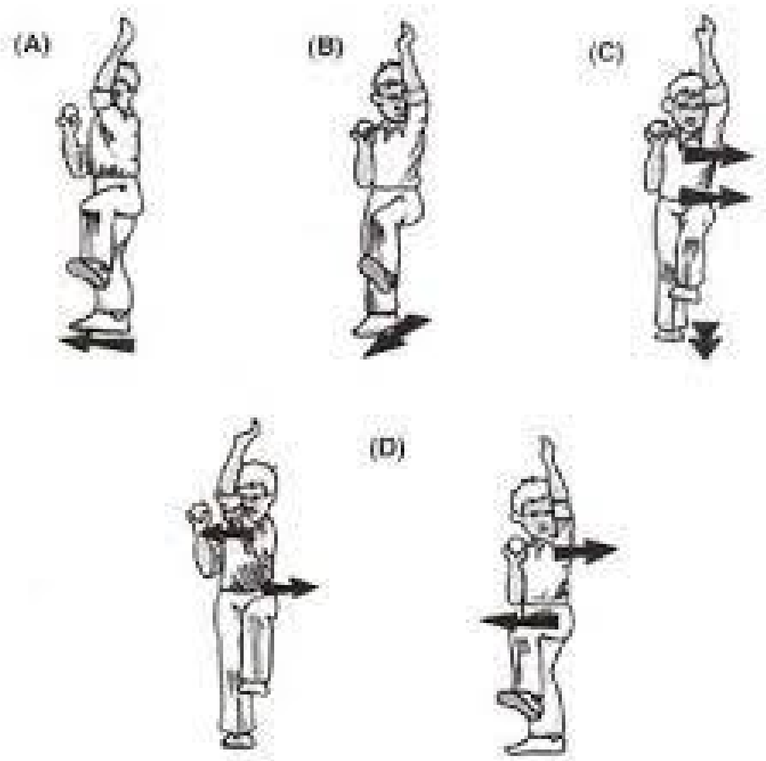


Figure 2.3: illustrations of (A) side on; (B) mid-way; (C) front on and (D) two mixed actions (taken from Portus et al., 2004).

Table 2.1: The explanation of fast bowling actions

action	shoulder alignment at BFC	pelvis – shoulder separation angle at BFC	shoulder counter rotation
side-on	<210º	$<30^{0}$	$<30^{0}$
mid-way	210º ≤ BFC ≤ 240º	$<30^{0}$	$<30^{0}$
front-on	>240º	$<30^{0}$	$<30^{0}$
mixed	not considered	$\geq 30^{0}$	$\geq 30^{0}$

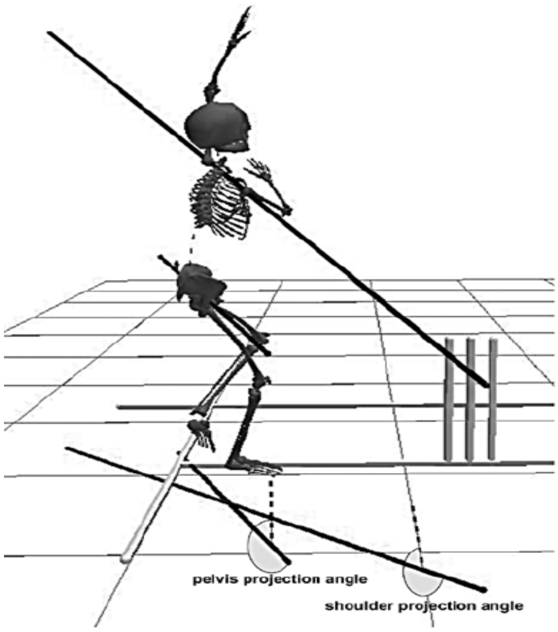


Figure 2.4: Pelvis - shoulder separation angle at BFC (taken from Worthington, 2010).

2.4 Back foot contact

At the end of the pre delivery stride, the bowler lands on the back foot and the orientation of it can differ from bowler to bowler as previously explained. A tight or a stiff back leg is required to propel the body forward and transfer the momentum forward towards front foot contact and ball release. The vertical force, however, acting on the bowler's during back foot contact can differ depending on the run-up speed (Hurrion et al., 2000) of the bowler.

Bowlers often are coached to lean backwards. The amount of backward leaning is dependent on the bowling action. Front on bowlers do not lean backwards as much as side on bowlers as their momentum is moving forward and no extra flexion is needed in the spine (Bartlett et al, 1996). When leaning backwards, side on bowlers are often compared to javelin throwers. At the end of a 3 step or 5 step run up in javelin, throwers lean back wards just before the start of the throwing arm movement (Bartlett and Best, 1988). The side on bowlers create lateral flexion of the spine, while front on bowlers create restrictive hyperextension (Penrose et al., 1976; Elliott et al., 1986). Mason et al. (1989) reported a 10º backwards lean and a 10º lateral flexion in junior bowlers at the instance of back foot contact. These findings were not clarified as they were not assigned into the action classification in the results. It has also been mentioned that front on bowlers need less backwards lean as they gather momentum more from the run up than the side on bowlers (Bartlett et al., 1996).

Different studies have suggested that the vertical force acting on the back foot is up to 2.9 times body weight (Mason et al, 1989; Saunders and Coleman, 1991) while the braking force is around 1 times bodyweight (Table 2.2).

Table 2.2: Summary of the findings in different studies on back foot contact

study	vertical force (BW)	braking force (BW)
Mason et al. (1989)	2.0	1.0
Saunders and Coleman (1991)	2.77	1.07
Elliott et al. (1992)	2.9 ± 0.8	1.1 ± 0.2
Hurrion et al. (2000)	2.37 ± 0.14	0.94 ± 0.16

2.5 Front foot contact

After the back foot contact phase, the delivery stride proceeds with the front foot contact phase. The front foot experiences more force in terms of the vertical and braking forces acting on the leg than the back foot (Elliott et al.,1992). An average of 4-6 times body weight has been recorded in previous studies. Mason et al. (1989) recorded a higher vertical reaction force at front foot contact value of 9 times body weight, but the literature hasn’t provided the exact details for this unfamiliar value. A summary of the findings is provided in the following table (Table 2.3) and example (Figure 2.5).

Table 2.3: Summary of the findings in different studies on front foot contact

study	vertical force (BW)	braking force (BW)
Elliot and Foster (1984)	4.7 ± 0.4	1.8 ± 0.3
Elliot and Foster (1985)	3.8	1.4
Elliot et al. (1986)	4.1 ± 0.9	1.6 ± 0.4
Foster et al. (1989)	5.43	2.45
Mason et al. (1989)	2.0	1.0
Saunders and Coleman (1991)	2.77	1.07
Elliott et al. (1992)	2.9 ± 0.8	1.1 ± 0.2
Elliott et al. (1993)	4.8 ± 1.4	2.1 ± 0.7
Hurrion et al. (1997a)	5.48 ± 1.08	2.17 ± 0.81
Hurrion et al. (1997b)	5.32 ± 1.40	2.47 ± 1.05
Hurrion et al. (2000)	2.37 ± 0.14	0.94 ± 0.16
Worthington (2010)	6.72 ± 1.42	4.47 ± 0.75

Simultaneously because of this higher ground reaction force acting on the body and specially in the lower body, injury concerns are much higher for a fast bowler than any other player. As this study mainly aims on finding out the kinematic variations among different ball lengths these injury patterns are not explained in this chapter.

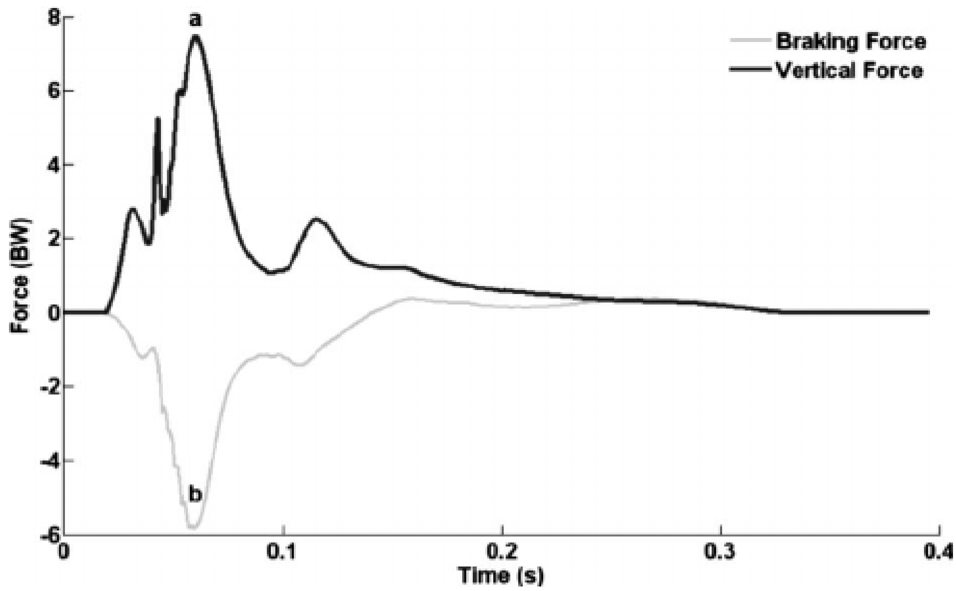


Figure 2.5: Vertical force and braking force acting at the instance of a typical front foot contact of a fast bowler (taken from Worthington, 2010).

2.6 Delivery stride

There have been many studies conducted in the delivery stride phase. The delivery stride starts with front foot contact and ends with the instant of ball release. Many studies have investigated this phase as it is associated with impacting ball release speed. These findings are summarised based on different elements of the technique below:

Plant angle and front foot strike

Worthington et al. (2013) described two new cricket specific parameters to analyse the motion of the front leg kinematics of a fast bowler. The plant angle was described by using the 2D Y-Z global coordinates of ankle and hip joint centres. The angle between the two lines joining the joint centres was taken as the plant angle. Similar definition was given to identify the foot-strike which is calculated by using the 2D Y-Z coordinates of MTP and ankle joint centres. The angle created by joining the joint centres and the global horizontal axis was named as the front foot strike. Both these parameters could explain the change of peak vertical force at front foot contact up to 41.2%.

Front knee angle

The front knee angle is a major kinematic parameter which most of the studies have concentrated on. Although an extended front knee angle has a positive corelation with the fast-bowling release speed it has had negative relationships in terms of lower back injury concerns. Davis and Blanksby (1976b) and Elliott and Foster (1984) have also recognised the front foot as a fulcrum to pivot the partially or fully extended front leg before the ball release. Some studies found that the extension of front knee during the front foot contact phase had a positive relationship with release speed (Portus et al., 2004), while some mentioned about the direct relationship of knee angle and ball release speed (Burden and Bartlett., 1990b). Moreover, the bowlers who did not flex at the front foot contact phase were much faster than rest of the bowlers which transfers the kinetic energy gathered by the bowler towards the ball (Elliott et al., 1986).

Worthington (2010) studied the front leg kinematics of fast bowling by identifying four main techniques with reference to the front knee angle which was described by Portus et al. (2004). These were:

Flexor – a knee flexion of 10º or more at the front foot flat instance and followed by less than another 10º of knee flexion before Ball release.

Extender – a knee flexion of less than 10º at the front foot flat instance and followed by a knee extension of 10º or more at BR

Flexor- extender – flexion and extension of the knee by 10º or more from front foot flat to ball release

Constant brace – both flexion and extension of the knee less than 10º from front foot flat to ball release

Although the front knee classification was used the results contradicted to what was found in previous studies. The relatively longer time taken to the peak vertical force by the flexor-extender knee bowlers was explained in the study to be due to them extending their knee when the front foot was flat, while increased vertical force was associated with greater knee flexion.

The bowling arm starts its circumduction around the shoulder joint with the elbow joint extended or closer to extended at a constant angle. The initiation of the upper (bowling) arm starts usually between back foot contact and front foot contact (Bartlett et al.,1996). The position of the bowling arm when the front foot contacts has been associated with bowling fast (Worthington et al., 2013). The fastest bowlers tend to delay the bowling arm as much as possible which will create a bigger angle between the shoulder and the upper trunk at front foot contact and ball release allowing increased trunk flexion and faster ball release speeds (Bartlett et al., 1996).

Trunk flexion

The amount of upper trunk flexion between front foot contact and the instance of ball release has been linked with increased ball release speed (Worthington et al., 2013). Although the study contradicted results from previous studies (Davis and Blanksby,1976; Elliot et al.,1986), the difference in results may have been due to the previous data being attained at low frequency. Bowlers who have larger trunk flexion were observed to have the fastest ball release speed. This technique mechanism has been suggested to be linked with bowling arm delay.

Bowling wrist and hand

The most distal joints of the arm, the wrist and fingers have also been considered in previous studies (Davis and Blanksby,1976b). The amount the ball will swing will highly depend on the finger and wrist position on the ball and shining one side will allow the flow of the wind to swing it on the air (Magias, 2015).

Non-bowling shoulder angle

The orientation and the action of the non-bowling arm is also important in making the ball faster. Pulling the non-bowling arm towards the trunk will create anticlockwise torques and will allow the centre of gravity to be stable and leaning forward. This will allow the hips to rotate the trunk at the delivery stride as well (Ferdinands, 2005).

2.7 Follow through

The follow through occurs at the end of the fast-bowling action after ball release where the bowler gradually reduces his speed after performing the high explosive activity. After ball release, the bowling arm will continue its circular path until it reaches the hip on the opposite side. The bowler will stop running after taking 2-3 steps to reduce the speed (Tyson, 1976). As this phase occurs after ball release there are very limited studies analysing it, as the importance of the follow through on the ball release speed has been considered minimal.

2.8 Cricket bowling variations

Fast bowlers tend to use a variety of different deliveries to attempt to dismiss batters in cricket. In modern-day limited overs cricket, different ball variations are the key as the batters use a higher amount of predetermined strokes when seeking quick runs. Bowlers can change the pace, length, and line of each delivery, as well as attempting to make the ball swing and seam (move off the pitch). Among these the terms stock, bouncer and yorker are used to define three completely different types of deliveries based on the pitching length of each.

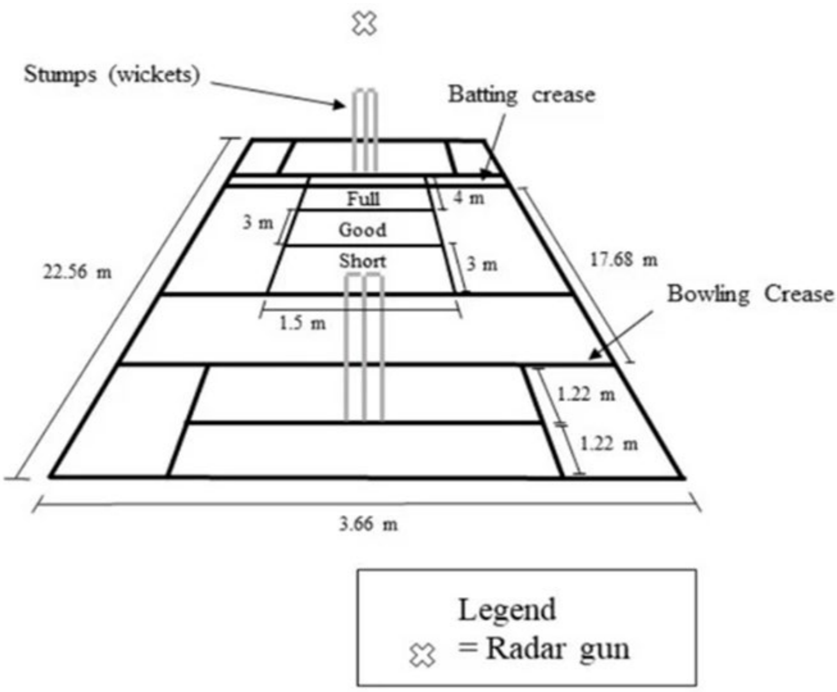


Figure 2.6: An illustration of pitch length variation explanation (taken from Callaghan et al., 2021).

A stock ball is a type of delivery which is bowled most frequently on a line and length which is considered as good (Figure 2.6). It is the most common and required length in a match. This length is adopted most frequently as batters are unsure whether to play the ball off the front foot or back foot. In previous investigations of pitch length delivery types, no significant changes in loading rates were found in 2 over spells of each delivery type (Callaghan et al., 2021).

A delivery that bounces relatively shorter (+7 m from the batting end stumps) and goes over the shoulder but below the top of the head of the batter who is in his batting stance is considered as a bouncer (Figure 2.6). A bouncer can surprise the batsmen and can be dangerous as well. According to the playing condition, a different number of bouncers are permitted in an over. In a limited overs match (one day international or a T20 international) only one bouncer is permitted in an over.

A yorker is a type of delivery used by cricket fast bowlers at different times in a match. A good yorker is bowled at the batter's feet approximately 0-2 m from the batting end stumps (Figure 2.6). The delivery is aimed at the batter's feet with the purpose of bouncing the ball at his feet making it difficult to execute a shot from his normal batting stance. A yorker, if implemented correctly, is hard to score runs from in the normal stance. A higher percentage of yorker balls are bowled in T20 cricket with a higher percentage of bouncers in test cricket (Justham et al., 2008). It takes a lot of practice to deliver a yorker to achieve substantial success and deliver it when needed. It has been found that winning teams often bowl more yorkers and bouncers than the losing teams in limited overs competitions (Najdan et al., 2014).

Muscle activity and fast bowling deliveries

While the current study does not intend to study EMG activity, it is useful to understand differences as they may indicate a difference in the kinematics and kinetics of the technique of each bowling delivery.

Ali (2016) discussed different types of muscle contractions occur in different muscle groups of the upper limbs at the delivery phase of fast bowling. Their study was mainly targeting the main three heads of the triceps brachii muscle as it has been shown to be the most active muscle group during fast and spin bowling during previous studies. The EMG analysis was completed across seven phases of fast bowling: the run-up, pre delivery stride, mid bound, back foot contact, front foot contact, ball release, and the follow through. Back foot contact, front foot contact and ball release phase generated more contractions in the triceps brachii, and the medial head was the most active among the three heads. Although the trials were not specifically identified, understanding the different EMG values in different deliveries can be useful in physical fitness and the strength and conditioning of bowlers.

Hazari (2015) studied the EMG activity in male fast bowlers at shoulder and wrist positions for predetermined yorker and bouncer delivery types. The data were captured by a coloured high-speed camera in the sagittal plane. Surface EMG was used in seven different muscles to record the activity in shoulder and wrist. The speed of the ball was not taken into consideration, but it was concluded that the biceps brachia providing the maximum electrical activity amongst the muscles for both yorker and bouncer. Furthermore, a significant difference in EMG activity was shown while bowling the yorker and the bouncer.

<u>Different research designs for investigating fast bowling</u>

Singh (2017) examined the height of the centre of gravity at delivery point on the performance of fast bowlers in cricket. 2D video graphic data was used for the study and significant association was shown between the ball release speed and height of the centre of gravity.

Salter (2007) examined different parameters which can affect the bowl release speed in with in bowlers and between bowler's methodologies. Two different analysis systems were used. The VICON motion analysis system for the between bowler analysis and the APAS analysis (Areal performance analysis system) was used to analyse the within bowler parameters which could be useful in affecting the bowl speed. Mainly the within bowler methodology was used to eliminate the anthropometric measurements and other physical differences between subjects, and therefore a steadier and a conclusive answer would be identified in the end. The within bowler analysis produced no relationships on the bowl pitch length and ball release speed. But in multiple stepwise regression analysis showed that 87.5% of the ball release speed can be explained by four technique parameters such as centre of mass velocity at back foot contact, maximum angular velocity of bowling humorous, vertical velocity of the non-bowling arm and stride length. Finally, no significant relationships were found on the between bowler methodology which again contradicts from the other studies done in the fast-bowling area.

Middleton et al. (2016) used cluster markers which were specifically made to avoid the tracking errors of the normal marker due high explosive movements and skin movements in fast bowling. Main target of the study was to identify the different lower limb kinematic values of two different fast bowling groups named as the high performance and the amateur. The high-performance group bowled significantly faster than the amateur group which was the main factor considered in dividing the groups. Not much difference was identified between the groups but faster centre of mass speed before back foot contact and withstanding a higher braking force which ultimately slow down the centre of mass speed at front foot contact allows bowlers to produce a higher speed.

Crewe et al. (2013) studied the lumbar-pelvic loading during the fast-bowling action and its relationship with the bowling speed and technique. A good length measured target was asked to bowl for all the subjects who participated in the study in pairs. The non-bowling subject had to complete a set of running, jogging, turning etc. activities to simulate the fielding activity. This method was used in previous studies as well. (Petersen, Pyne, Dawson, Portus, and Kellett, 2010). This was used to keep the bowler warmed up even during non-bowling times as it creates a real match situation. Two successful fastest deliveries from each over was considered for the analysis. In the analysis although it was found that there was no significant difference in technique in an eight over long spell, A straighter front knee, faster ball release speed and increased shoulder counter-rotation were related to aspects of lumbo-pelvic loading – peak transverse plane rotation moments and anterior-posterior shear forces.

2.9 Variations in body kinematics used in other sports involving throwing or swinging action

Tennis serves

Tennis serves are similar to many overhead athletic movements, and as the serve plays the most important and most complex role in competitive tennis, it has been heavily analysed.

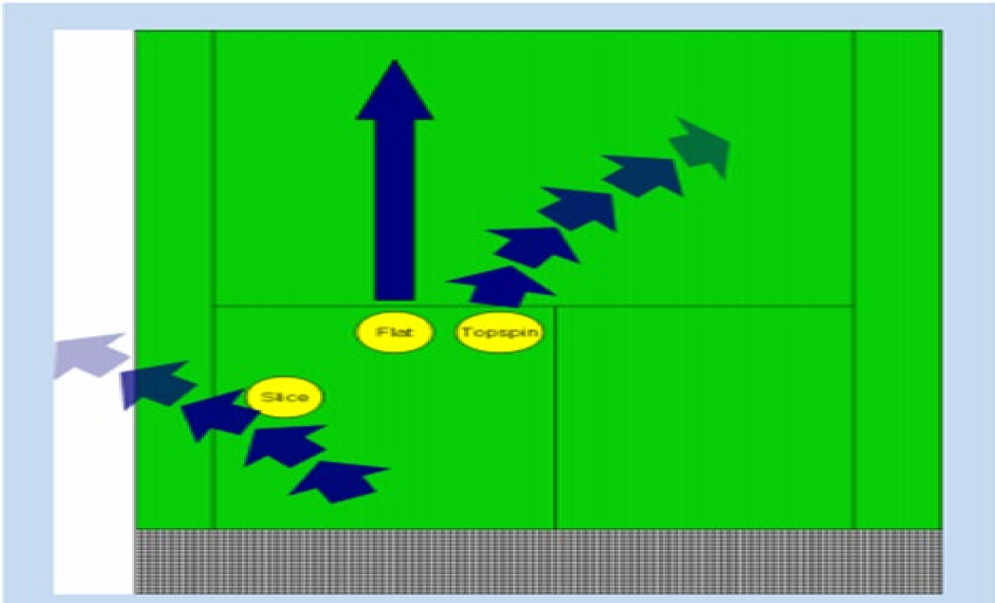


Figure 2.7: Three main types of tennis serve (taken from Kovacs, 2011).

Kovacs (2011) investigated the tennis serve using an eight-stage model. The purpose of the study was to identify key performance enhancers and injury patterns in three different variations: slice, flat, and topspin (Figure 2.7). Secondary data from 1980 to 2010 was used for this study. Movements of the tennis serves associated with limb and joint movements to generate forces from the ground, its transfer through the kinetic chain and to hit the ball were analysed. The study identified key instances of the tennis serve and analysed the key differences occur starting from the loading phase to the deceleration phase after the contact. Kinematic variances, kinetic variances and muscle activation variances were compared among the three service variations. The lower body movement of these 3 serves were most similar to one another. Rectus abdomen and external oblique muscle activation, however, showed differences within muscle activation in the loading phase. Various kinematic differences were observed across the different phases between serves, and differences in the knee angle were found between foot up and foot back techniques. Later in the service at the acceleration and contact phases more changes were highlighted in the elbow and shoulder joints while muscle activation differences were displayed in pectoralis major, latissimus dorsi and subscapularis muscles among the three service variations.

Baseball pitching

Baseball pitching is another overhead athletic movement which utilises different variations. Stodden (2005) investigated the relationship between biomechanical factors and baseball pitching velocity (within pitcher variation). The main objective of this article was to analyse the relationship between baseball fastball velocity and different throwing mechanics. Nineteen baseball pitchers pitched different types of throws. Motion analysis expert vision 3D software and a direct linear transformation (DLT) method were used to calculate three-dimensional marker locations. Variables were analysed between front foot contact and just after ball release. Forces and torques acting on the shoulder and elbow were calculated and analysed (Figure 2.8). The analysis found eleven temporal parameters related to joint/segment angular and linear velocities. Elbow flexion torque was the main kinetic parameter behind pitch variations. Horizontal abduction and time to maximum internal rotation velocity was also showed significant variances among pitch variations.

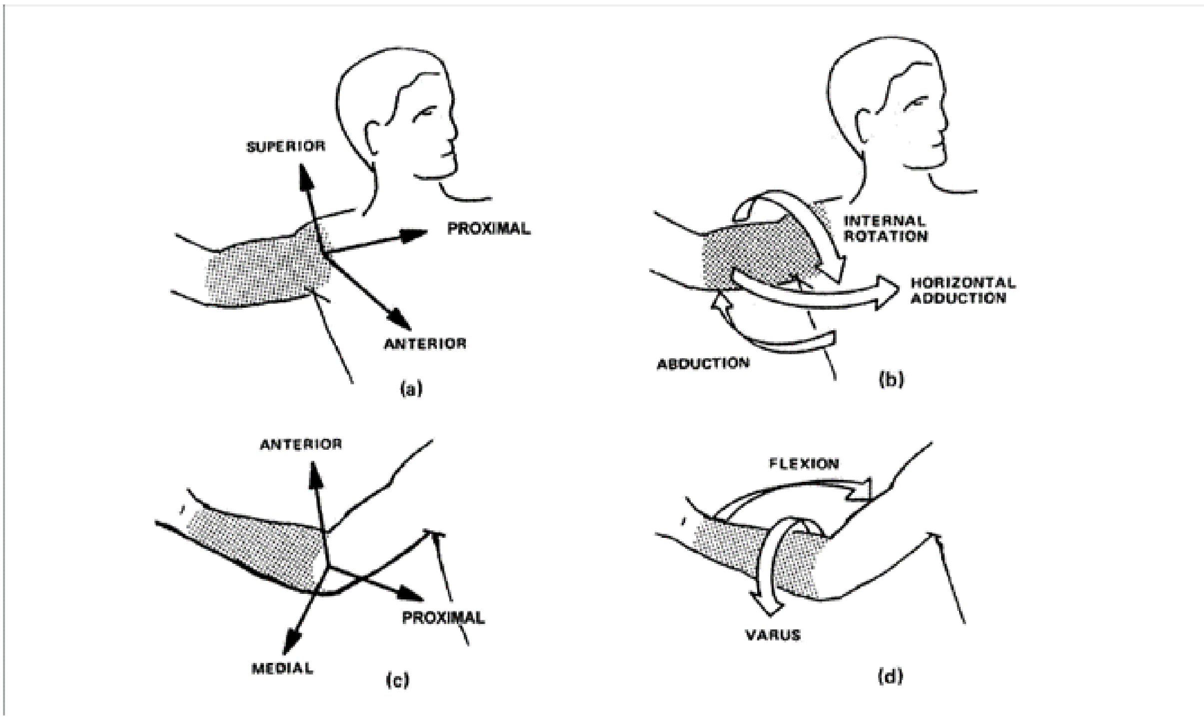


Figure 2.8: Distal and proximal ends of the joint centres used for calculating kinetics (taken from Strodden, 2005).

Javelin throw

Bartonietz (2008) investigated javelin throwing variations and the distance differences. Previous studies data were used in conducting this study. Similar to cricket fast bowling, the throwing distance is based on the javelins release velocity, height of the release point, release angle, and the direction of the release velocity (Figure 2.9). Other factors including the angle of attack, angle of yaw, momentum of initial pitching, air condition, and revolutions of the javelin around the longitudinal axis and vibration amplitude of javelin were also analysed and shown to impact throwing distance. Although angle of yaw and revolutions around long axis were considered in this study it is not applicable to circular object. Different kinematics such as knee angle and front leg plant angle directly affect the throwing mechanics but are not relevant to this study as there are no clearly defined variations in javelin throw.

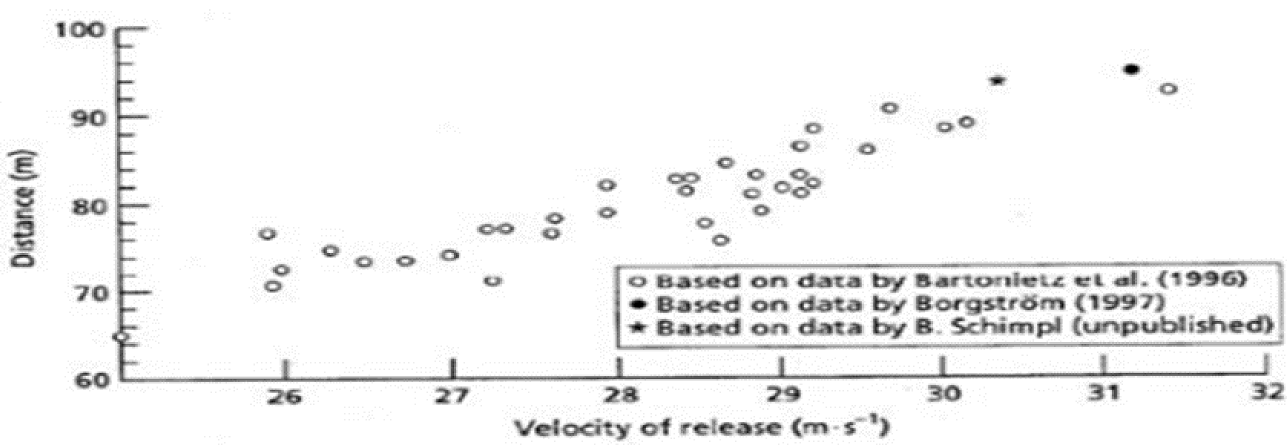


Figure 2.9: Stats of previous studies used by Bartonietz for distance and release velocity (taken from Bartonietz, 2008).

2.10 Ball - finger mechanics and release conditions

Ball release mechanics plays a huge role in deciding the pitch length of the ball as it directly influences the path of the ball after release. To achieve accuracy, ball release must occur at the right point on this hand path. This is partly determined at the point on the hand path where the ball is first released from the handgrip. Once it is released from the handgrip, the ball rolls along the fingers until final release from the fingertip as the hand moves under the ball (Hore et al., 1999b). Final ball direction is established about halfway through this release period (Watts et al., 2004).

In previous studies when deciding the ball release instance for overarm throws a variety of measurements have been used. Identifying the last moment that the finger can influence the path of the ball is likely to be key in this kind of analysis (Hore et al., 1996a). Some methods to determine this have included using triggers at the proximal and distal phalanges or calculating the movement in the displacement between a point on the hand (fingers, palm or wrist) and the ball. Although ball release angle has been considered in previous fast bowling biomechanics studies, ball finger mechanics have not been considered as the pitch length variation studies are scarce.

2.11 Chapter summary

Previous biomechanical studies investigating the performance of fast bowling have almost predominately investigated ball release speed. Recently with the increased amount and value of winning in limited overs cricket, studies have started to investigate the variations of fast bowling. Although preliminary research in this area has investigated muscle activity and loading rates for different length variations, no study has investigated the kinematic changes. This study will use three-dimensional kinematic and kinetic analysis to identify the key technique changes among the different length variations.

CHAPTER 3

DATA COLLECTION METHODOLOGY

This chapter explains the methods and the equipment used to collect the kinetic and kinematic data along with anthropometric measurements for each participant in the study. The procedure from player calibration to data processing for analysis is explained in this chapter.

3.1 Equipment

Data were collected over four separate data collection sessions (October 2020 to December 2020) at the National Centre for Sport and Exercise Medicine (NCSEM) Biomechanics laboratory, Loughborough University. The indoor facility allowed participants to bowl using their normal run-up on a standard sized, artificial cricket pitch (Figure 3.1). Two Kistler force plates (Type 9287B – 900 x 600 mm, 1000 Hz) were permanently installed in the facility and located at the bowling crease.

Figure 3.1: The data collection laboratory.

An 18 camera Vicon Motion Analysis System (OMG Plc, Oxford UK) was used to collect the kinematic bowling data. Eighteen cameras (MX13) which were operating at a frequency of 250 Hz, were positioned to cover a volume of approximately 6 x 3 x 3 m (Figure 3.1). These cameras were in fixed positions in the laboratory. A cricket net was used to surround the pitch area which kept the ball inside the concentrated area and prevented damaging other equipment in the laboratory.

The Vicon motion analysis system was calibrated at the start of each day of data collection using a calibration wand (14 mm markers) to define the origin and global coordinate system. The global origin was located at the back left corner of the force plate. The x axis was pointed from left to right, y axis from bowling end to the batting end, which was anterior, z axis pointed vertically upwards.

In addition to that, four 2D Bonita cameras (recorded at 250 Hz) were used to capture the bowling actions for further analysis and reference in future (Figures 3.2, 3.3, 3.4, 3.5). These eighteen Vicon cameras, four Bonita 2D cameras and the Kistler force plate were connected to the Vicon Motion analysis system. Therefore, all were synced automatically to start and stop together on given commands. The Bonita cameras were placed; one on the right side at the bowling end crease for the side on view (Figure 3.3), one at the back of the run up for the posterior view (Figure 3.5), one at the top of the batting end stumps for the anterior view (Figure 3.4) and one on the top of bowling crease to capture the motion from a downward view (Figure 3.2).

Figure 3.2: View from the top of the bowler from bowling end stumps.

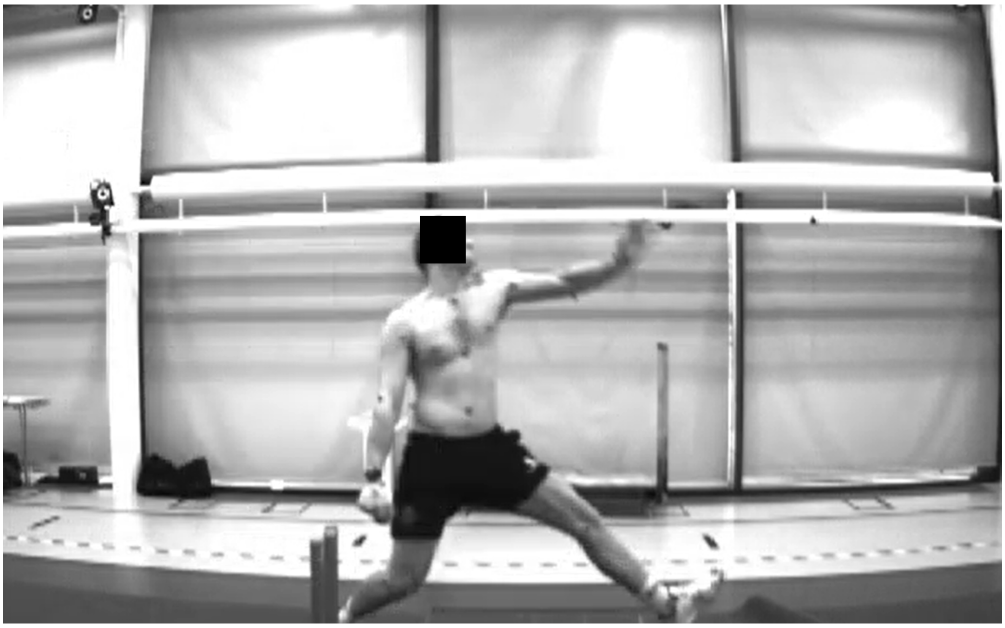


Figure 3.3: Sagittal plane view from bowling end stumps.

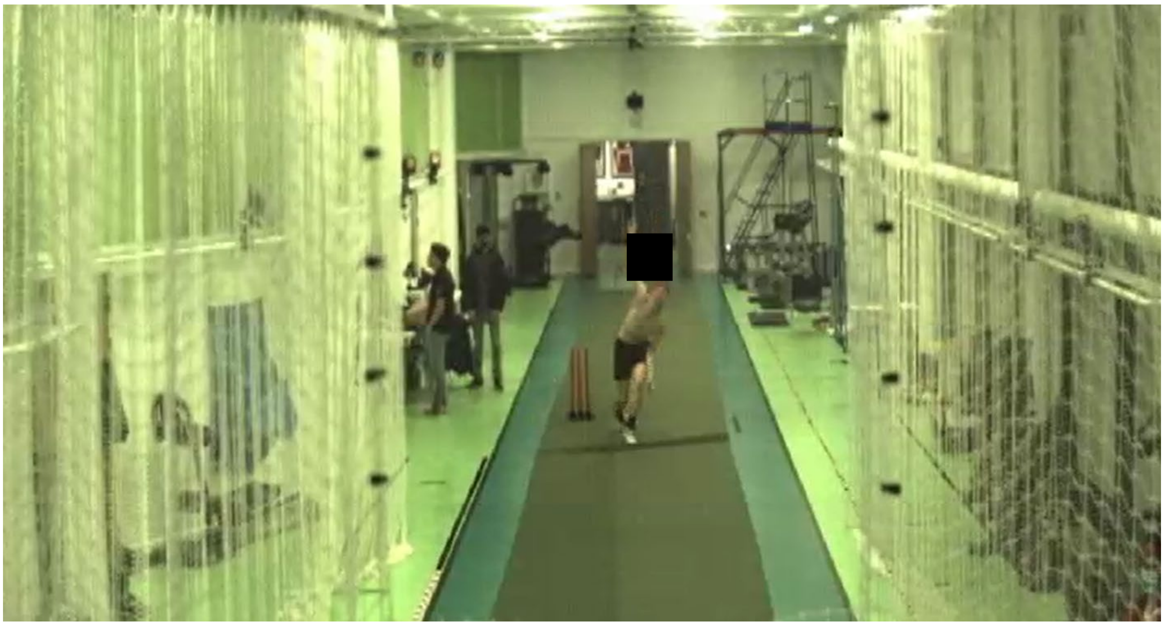


Figure 3.4: Top of the batting end stumps for the anterior view.

Figure 3.5: Frontal plane view from the back of the bowler.

3.2 Participants

Twenty-one fast bowlers were voluntarily tested over the course of the four data collection sessions (mean ± standard deviation: age 19 ± 2 years; height 1.86 ± 0.05 m; body mass 81.4 ± 9.7 kg). All bowlers were chosen from MCCU squad and county academy, identified as "fast bowlers". These bowlers were deemed fit by their team physiotherapists (**See Appendix 3 for details of height, weight, and age of all the bowlers in the study**).

The testing procedures were explained to each bowler in accordance with Loughborough University ethical guidelines and informed consent form was signed (**Appendix 1 and 2**). All bowlers conducted an adequate warm-up soon after the anthropometric measurements were collected. A skilled researcher used a tape measure and ruler to take 95 anthropometric measures (**Appendix 4**).

To divide the body into 18 segments, markers were placed at specified locations and comprised lengths, widths, depths, and perimeters. This made it possible to employ segmental density values from Chandler et al. in Yeadon's geometric model (Yeadon, 1990a) to determine subject-specific segmental inertia parameters. After finishing a personal warm-up, the participant was checked for any missing or loose markings before performing static trials on the force plate. A static anatomical position was used to calculate the lengths of body segments and the degrees of joint offsets. Following a demonstration, participants underwent three range-of-motion trials to the limit of their active lower trunk flexion and extension, lateral flexion to both sides, and rotation to both sides, all while maintaining a static pelvis, straight legs, flat feet, and an upright posture (Figure 3.5). This adhered to the Ranson et al. (2008) methodology to enable determination of neutral spine position and lower back range of motion (lower back reference frame relative to the pelvis reference frame).

All the subjects then bowled 48 deliveries (8 overs) which consisted of) 12 yorkers, 12 bouncers and 24 stock balls (12 for right-handed batsmen and 12 for left-handed batsmen in a randomised order. Each subject was given an appropriate rest after each 12 trials to minimise fatigue. Only a few trials were not used in the analysis; when a subject failed to perform the bowling sequence at least up to ball release instance without losing any crucial markers (e.g.: bowling arm markers) which fell off during the explosive fast bowling action. The following distances of the pitch from the batting end stumps were considered for the classification of delivery type (Hazari, 2016):

0-2 m: yorker
4-7 m: stock ball
> 7 m: bouncer

3.3 Markers

Fifty-three 14 mm retro-reflective markers were attached to each bowler using a sports adhesive spray and double-sided tape. Markers were positioned over bony landmarks in accordance with the marker set previously used by Worthington (Worthington, 2010). This marker set has been used for many fast-bowling studies investigating performance lower back injuries (Figure 3.6). Details of the marker positions and calculations are explained in Chapter 4 and provided in Appendix 6.

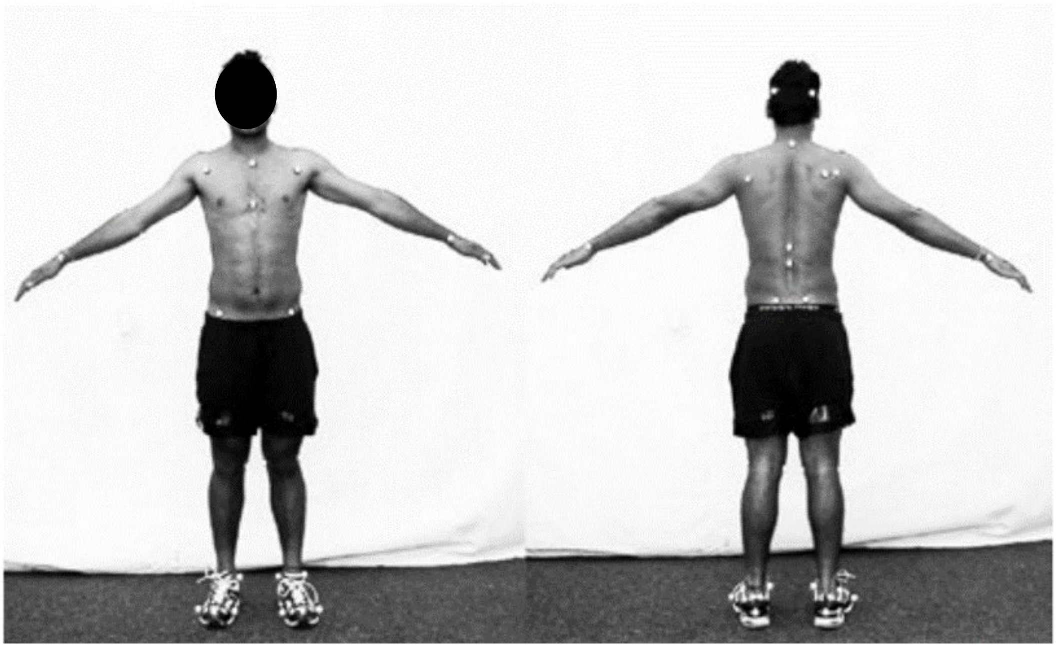
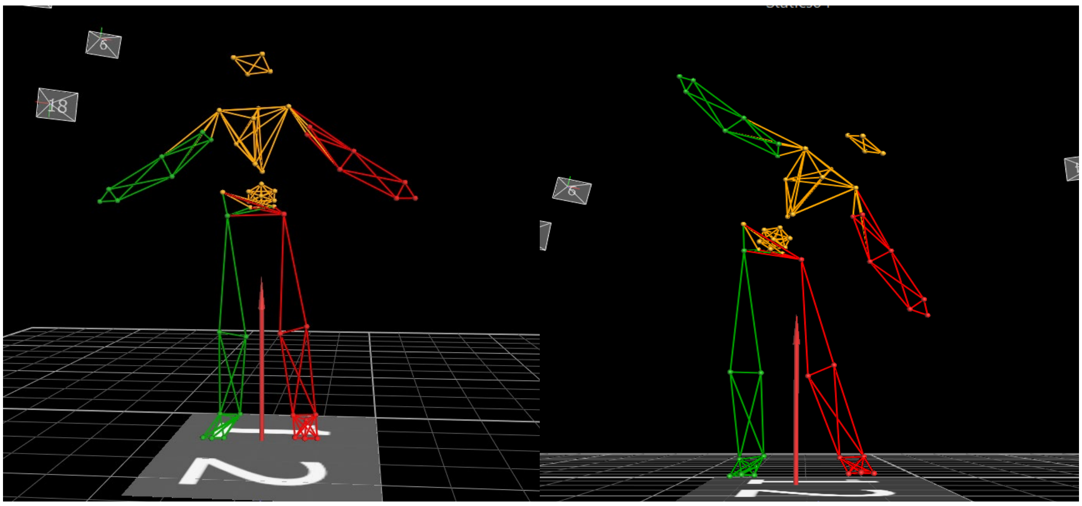


Figure 3.6: Two images of a player with all the markers attached (taken from Worthington et al., 2022).

Two additional markers, in the form of 15 x 15 mm patches of 3M Scotch-Lite reflective tape were attached to the halves of the ball (Figure 3.7). This helped in identifying the ball path throughout the activity. Ball markers were used in identifying the ball release instance, ball release speed, and ball release angle in different parts of the analysis.

Figure 3.7: An image of a ball marker used in the trials (taken from Worthington, 2010).



a) **b)**

Figure 3.8: A labelled Vicon view, a) static and b) range of motion (side flexion) trial of the fifty-three markers used.

3.4 Data labelling and gap filling

Data labelling and gap filling is a major part in studies using three-dimensional motion capture analysis. Prior to data labelling, a suitable 3D model (Worthington, 2010; Alway et al., 2020) was attached to each trial which was specifically developed for analysing fast bowlers.

Fast bowling trials were captured with the bowler using a full-length run-up to a steady state of the bowler after ball release. As the player starts the run-up outside the capture volume and finishes their delivery outside the volume (6 x 3 x 3 m), the frames in the earlier and later parts of the action did not fully capture the markers but were fine within the capture volume. During the trial, every possible effort was made to secure all the markers from the start to the finish. However, due to the speed of the fast-bowling activity it was inevitable that some of the markers would fall off in numerous trials which leaves gaps in the marker time histories (Figure 3.9). Since the main consideration was the motion from back foot contact to ball release, the other parts of the trials were cropped. Every possible effort was made to get at least 18 frames before the back foot contact and at least 10 frames just after the ball release to calculate the run-up speed and ball release speed. Only a few gaps were present in the specific period of the bowling action which was analysed.

These gaps were filled using the “Pattern fill” function within Vicon’s Bodybuilder software (version 2.10) for most of the occasions. The “Rigid body fill” function was also used for filling the gaps if the gap was from a marker in the head region or a marker from the pelvis area. Only pelvis and head segments were filled using this specific gap filling method as it requires three other markers moving closely and together to calculate the missing marker. In each gap filling occasion, the filled data were visually inspected.

The maximum possible trials were taken for the analysis out of the thirty- six trials which were considered. Although forty-eight full length run up deliveries were performed only one of either of the sets of twelve stock balls were selected depending on the ability to pitch the ball in the predetermined area. Some bowlers did struggle to pitch the ball in the correct area depending on the assumed batsmen’s hand.

Trials were excluded only if necessary; markers were missing at key instances or if the bowler didn’t land his front foot fully on the force plate.

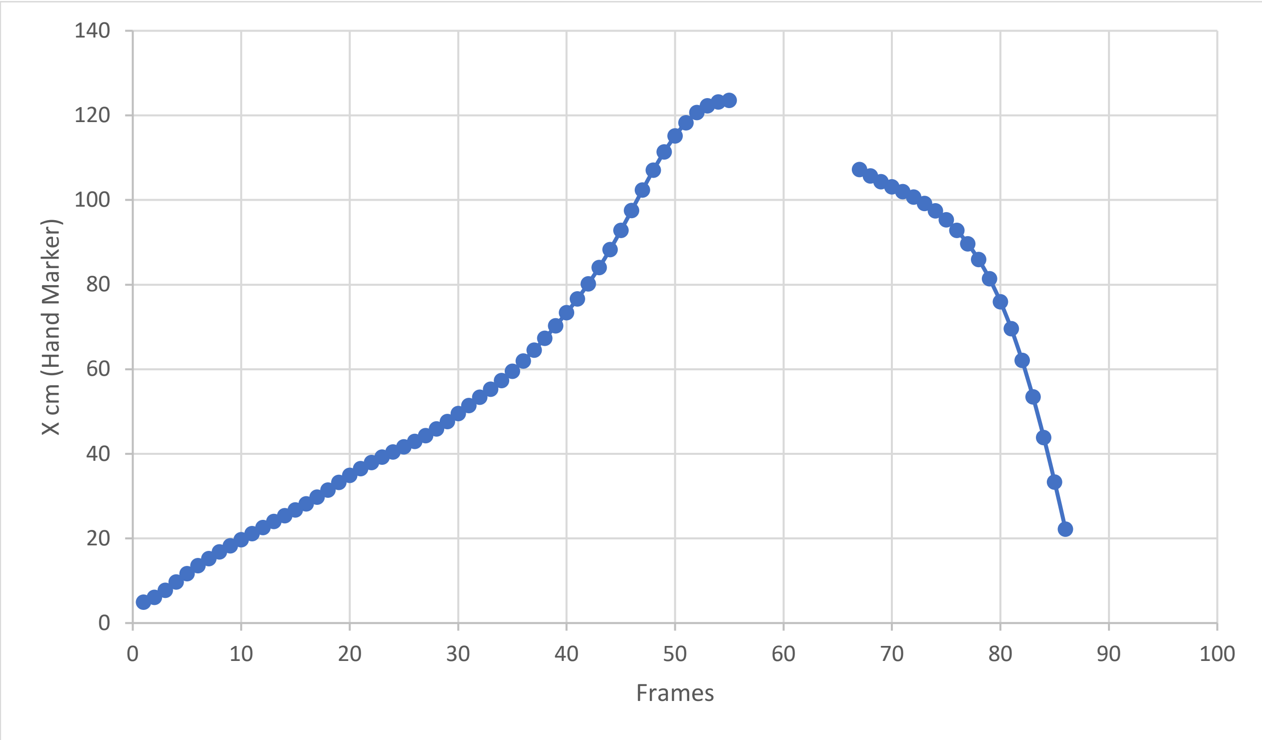


Figure 3.9: Example of a gap in a trajectory.

3.5 Identification of key instants

Back foot contact was identified using the three-dimensional trajectories of the markers on the right or left foot as the instant where the foot marker was visually seen to change its motion due to contact with the ground. The key instances were manually identified using the motions of the markers; back foot contact was identified using the sudden change of the orientation of MTP markers of the back foot, front foot contact was identified with the help of the force platform (when ground reaction force exceeded 25 N (Worthington et al., 2013)). Finally, ball release was defined as when the distance between the hand and middle of ball markers exceeded 20 mm in consecutive two frames (Worthington et al., 2013), Figure 3.10).

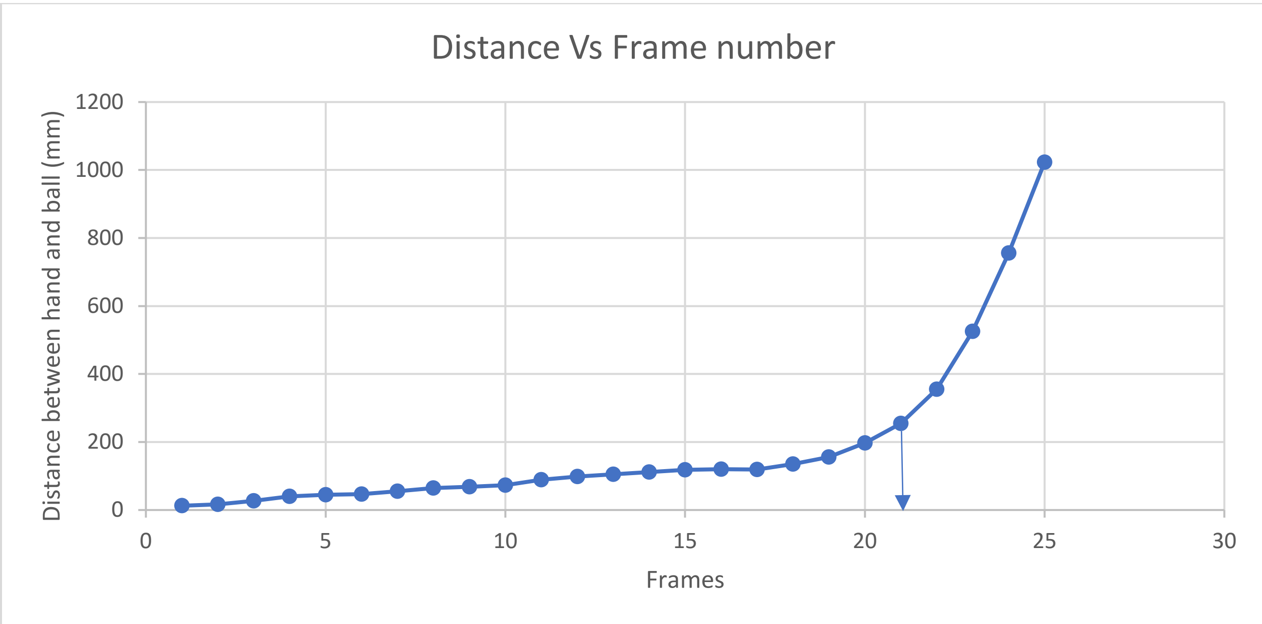
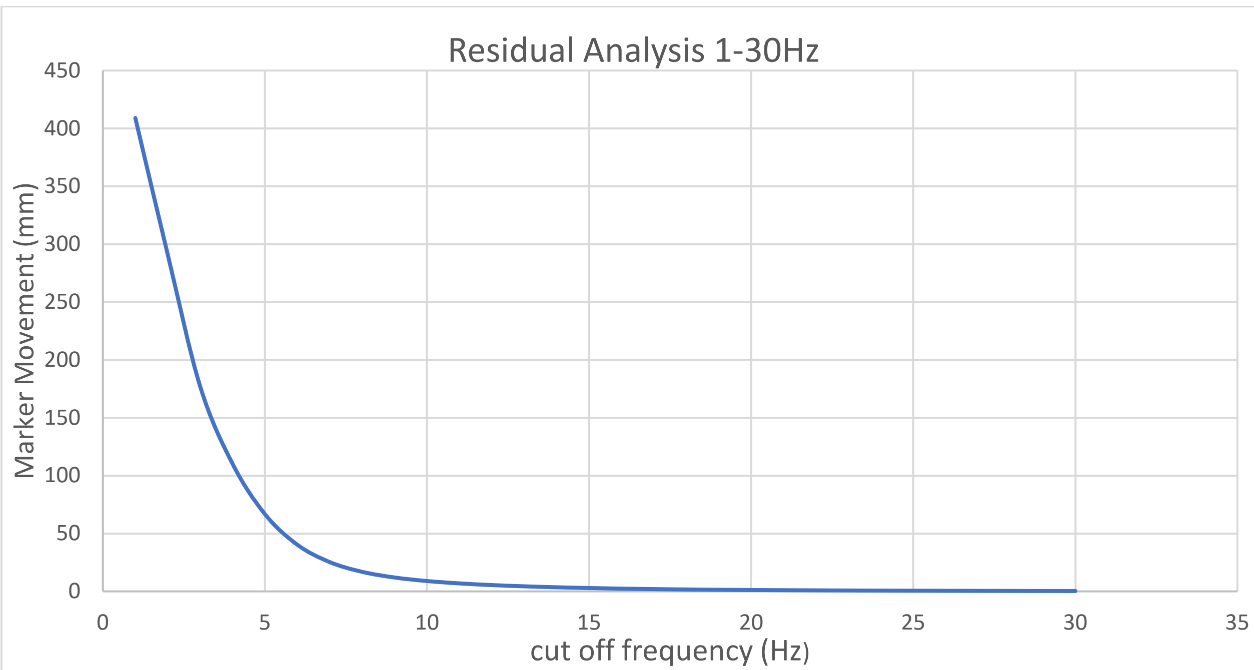


Figure 3.10: A graph of distance between the marker (in mm) on the ball and middle of hand marker.

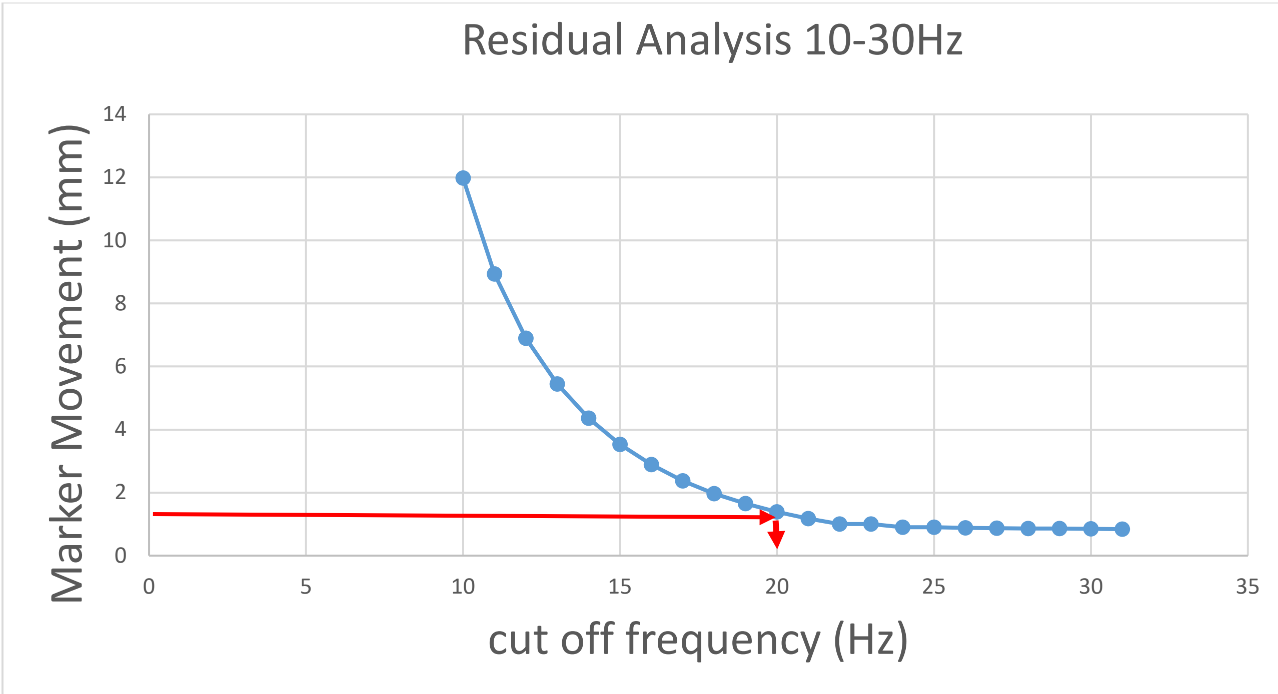
3.6 Filtering

All marker trajectories (except the ball marker) were filtered using a fourth order lower pass Butterworth filter with a cut off frequency of 20 Hz (Figure 3.11) which was decided after performing a residual analysis. This method was suggested by Winter (1990) and was used in previous studies as well (Worthington, 2013; Alway et al., 2020).

This reduced the noise in the velocities and accelerations but made little difference to the position of the markers.



(a)



(b)

Figure 3.11: Residual analysis performed (a) 1- 30 Hz and (b) cropped 10 – 30 Hz to identify the suitable cut off frequency.

3.7 Chapter summary

This methodology chapter has provided details of the testing procedures used in all the data collection sessions and details of the participants involved in this study. The data processing procedure including the selection and omission criteria of trials is described. The methods used to fill gaps in the marker trajectories has been illustrated and the level of filtering justified in this chapter.

CHAPTER 4

DATA ANALYSIS

4.1 Introduction

This chapter describes the data analysis procedures after the data was exported from the motion analysis software (VICON, version 2.10).

4.2 Data analysis procedure

Some trials were able to be used in all analyses, but some trials could only be used for some of the studies. As an example, if a marker at the elbow was missing throughout the trial, the trial was not considered for joint angle analysis, but it was used for investigating the pitch length vs ball release angle/speed/ height analysis only.

4.3 DLT Procedure

The Direct linear transformation (DLT) method was used to calculate the ball landing position for each delivery bowled. For the first research question in Chapter 5, it was intended to find out how well the bowlers can control their length. For this purpose, it was needed to estimate the ball pitch length for each delivery.

Although the ball pitch length was taken from both visual estimation and using constant acceleration equations, these data were compared with the 2D video analysis as well. As the Vicon calibrated area is 6 x 3 x 3 m, it was not possible to record the ball pitch length position directly. Therefore, to record the ball landing position, the Bonita camera (operating at 250 Hz) at the back of the bowler was used to get these landing positions. The pitch was marked with white chalk lines every 2 m up to 12 m from the batting end stumps.

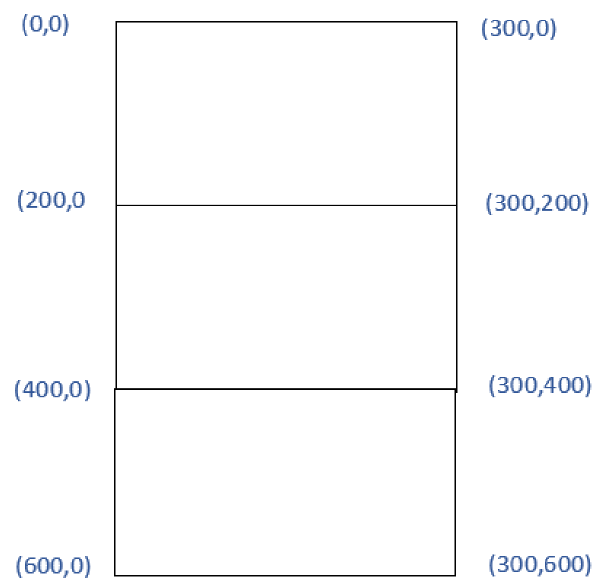


Figure 4.1: Eight digitised points (ball was also digitised) in the 2D image plan coordinate system in the ball pitch analysis.

In the DLT calculations normally a minimum of fourteen calibration points are needed to get the X, Y, Z coordinates of a new unknown location (Abdel-Aziz, 2015). But for this analysis the Z coordinate becomes zero as the landing location is needed. Therefore, only eight calibration points are needed to find out the unknown ball pitch length coordinate.

In addition to these eight known coordinates, the specific image where the ball was in contact with the pitch was digitised using Silicon Coach software (Live version 6.5.1.0, siliconCOACH Ltd, Dunedin) to get the ball pitch position in global coordinates of the cricket pitch. To reduce human errors when selecting and clicking on the calibration points each video was digitised three times. The average pixel coordinates were then used as the input values.

These calibration pixel coordinates along with the ball pixel coordinates were then used in a MATLAB (2017a, The MathWorks, Inc) algorithm which implements the 2D direct linear transformation. Therefore, ball coordinates were given in the global reference system as the output of this MATLAB algorithm.

Furthermore, as explained earlier the direct linear transformation is a method designed to calculate eleven parameters which gives the relationship between the object or the global reference system (GRS) and the image-plane reference system. Although in this study, as the Z component was assumed to be zero, the number of direct linear transformation calibration parameters needed was eight. (Shapiro, 1978; Abdel-Aziz, 2015)

4.4 Rigid body segment representation of the bowler

The fifty-three markers attached to the bowler's body represented different rigid segments of the body. Previous studies have divided the body into different a number of rigid body segments depending on the analyses. In this study, only the wrist, shoulder and the thoracic and knee joint kinematics and torques were investigated. Furthermore, as the spine has different degrees of movements in various parts it is more complex to understand and investigate.

In this study, although the trunk was divided into lumbar, thoracic, and cervical segments only the thoracic angle in the sagittal plane (flexion and extension) was considered for analysis. Then, a three-dimensional segment coordinate system (local coordinate system) was defined as detailed below to analyse each segment for joint angles and joint torques. A MATLAB script was used to calculate these kinematic and kinetic results.

Joint centre locations

Most joints had two markers, placed one on each of the medial and lateral aspects (or anterior and posterior for the shoulders), which were positioned across the joint by an experienced researcher. The midpoint of these markers was considered as the joint centre location for analysis. Although most of the joints were analysed using this method, exceptions were made for the hips and back segments as explained earlier.

The right and left hip joint centres were calculated using the following algorithm of Davis et al. (1991):

For Right hip joint centre

X = (-1) *[C*sin (28.4) – d/2]

Y = {[(-0.0001288*LegLength) – 0.04856] – [0.014]} *cos (18) + C*cos(28.4) *sin (18)

Z = {[(-0.0001288*LegLength) – 0.04856] – [0.014]} *sin (18) + C*cos(28.4) *cos (18)

For Left hip joint centre

X = [C*sin (28.4) – d/2]

Y = {[(-0.0001288*LegLength) – 0.04856] – [0.014]} *cos (18) + C*cos(28.4) *sin (18)

Z = {[(-0.0001288*LegLength) – 0.04856] – [0.014]} *sin (18) + C*cos(28.4) *cos (18)

- C = (0.115*LegLength – 0.0153)
- d = distance between the right and left anterior super iliac markers
- LegLength = average of the distance of both legs from hip joint centre to lateral ankle marker along the lateral knee marker

Joint centre locations in the back were calculated using the methodology of Roosen (2007):

Lower back joint centre = SACR + 0.2*(PELF-SACR)

Mid back joint centre = T10 + 0.125* (FThorax – BThorax)

Top joint centre = C7 + 0.125* (C7 – CLAV)

- SACR = (RPSI + LPSI) / 2
- PELF = (RASI + LASI) / 2
- FThorax = (CLAV + STRN) / 2
- BThorax = (C7 + T10) / 2

- [RPSI – Right posterior super iliac, LPSI – Left posterior super iliac, RASI – Right anterior super iliac, LASI – Left anterior super iliac, CLAV – proximal end of sternum, STRN – distal end of sternum, C7 and T10 – spinous process of both C7 and T10]

Rigid body segments definitions

Eighteen segments were defined each using a local coordinate system. These segments were defined with the player standing in an anatomical position. The positive z axis pointed upwards along the longitudinal axis of the segment, with rotation about this axis representing internal/external rotation. The positive y axis was pointing forwards, with rotations about this axis representing abduction/ adduction. The positive x axis pointed to the bowlers right representing flexion/ extension movements occur during the fast-bowling action.

Angle definitions

Joint angles were calculated using the cardan angles which described the orientation of a rigid body segment in space. Rotation angles were calculated in an xyz sequence corresponding to flexion/extension, abduction/adduction, and internal/external rotation movements respectively. Only x axis rotations (flexion/ extension) were considered when comparing bowling length conditions.

Table 4.1: Joint angle definitions

joint angle	positive movement	anatomical position angle (^{0})
knee angle	extension	180^0
thoracic angle	extension	180^0
shoulder angle	flexion	0^0
wrist angle	extension	180^0

Centre of mass and moment of inertia calculation

Ninety-five anthropometric measurements were taken at specific positions including lengths, widths and depths and perimeters on the body by an experienced researcher. This helped in determining subject-specific inertia parameters and centre of mass using them in Yeadon's (1990) geometric model.

Internal forces and joint moments were calculated at the proximal joint (origin of each segment) using the rigid segment model and an inverse dynamics approach. An additional mass of the ball (159 g) was considered halfway between the bowling hand's knuckles and fingernails within the model.

4.5 Kinetic parameters and Inverse dynamics calculation

Using the force data gathered by Kistler's Bioware program, descriptive parameters for the ground response forces during the front foot contact phase were derived. These variables comprised the maximum forces in the horizontal (braking) and vertical directions, as well as the interval between the initial contact of the front foot and the occurrence of the maximum forces. The peak horizontal loading rate (PHLR), peak vertical loading rate (PVLR), and average rate of loading for both directions were computed. Additionally, the horizontal and vertical impulses applied during the front foot contact period until the ball release were calculated.

Inverse dynamics calculations carried out within MATLAB determined the forces and moments acting at each joint within the 18-segment system. Each segment was used in a top-down method (Vlietstra, 2014) to calculate joint moments acting on each proximal end of the segments. The ground reaction force was considered only for calculating ground reaction force parameters. Using the local coordinate system of the child segment at each joint, the inverse dynamics procedure determined the internal joint forces and moments operating on the child segment at each joint. Positive forces moved in the coordinate axes' direction, and positive moments moved counterclockwise around the axes (Figure 4.2).

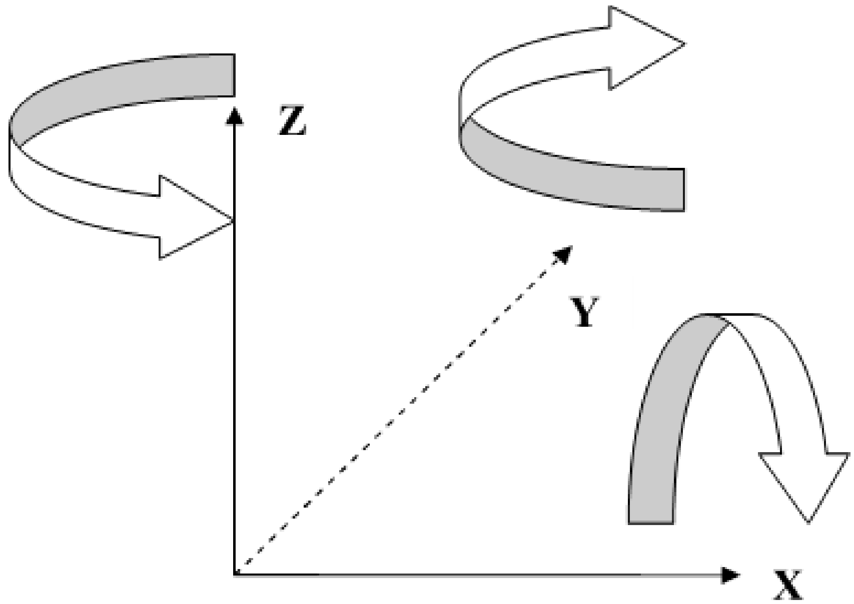


Figure 4.2: Direction of positive forces and moments (taken from Worthington, 2013).

Run up speed calculation

Bowling run up speed is a major parameter in deciding the momentum the ball has just before the delivery step. The last 18 frames just before the back foot contact frame was considered for the calculation of average velocity. Although the bowlers use different approaches using accelerations and decelerations during the run up phase, it was assumed that the centre of mass of the bowler was moving in linear relatively constant velocity in this 18 frames time duration. The horizontal velocity of the player in the direction towards the batter was calculated using the following simple linear motion equation.

$$S = U * t \longrightarrow U = S/t$$

S = distance of the centre of mass has travelled during the 18 frames

t = time difference for 18 frames which is 18/250 s = 0.072 s

U = Average velocity of the centre of mass of the bowler

Ball release speed calculation

Similar to the run-up speed, simple linear motion equations were used to calculate the ball release speed. The ball was assumed to move in constant velocity in x and y directions (assuming negligible air resistance) while vertical velocity (z) was calculated using constant acceleration equation. The resultant ball release speed was calculated from the 3 separate directions. 10 frames after ball release were considered for the calculation.

X direction and Y direction velocities were calculated using general linear motion equations:

$$S = U * t \longrightarrow U = S/t$$

S = Distance the ball marker has travelled during the 10 frames

t = time difference for 10 frames which is 10/250 s = 0.04 s

U = Average horizontal velocity of the ball

Vertical speed was also calculated, including consideration of acceleration due to gravity:

$$S = U_1 * t + ½ * a * t^2 \longrightarrow u_1 = S/t - ½ * a * t$$

S = vertical distance the ball marker which travelled during the 10 frames

t = time difference for 10 frames which is 10/250 s = 0.04 s

a = gravitational acceleration g= 9.8 ms^{-2}

U = starting vertical velocity of the ball

Ball release height

Ball release height was defined as the z coordinate of the ball marker at the point of ball release. The ball release instant was defined as when the distance between the hand and middle of ball markers exceeded 20 mm in consecutive two frames.

Ball release angle

Ball release angle was calculated using the horizontal and vertical release speed measures. The arctangent between the vectors will provide the release angle in each trial:

$$\mathrm{Tan}\ \alpha = u_{1}/u \longrightarrow \alpha = \tan^{-1}(u_1/u)$$

α = ball release angle

u_1 = starting vertical velocity

u = horizontal velocity

4.6 Statistical analysis

Statistical Package for the Social Sciences (SPSS Corporation, USA v 25) was used to conduct all statistical analyses. As the release parameter data were normally distributed [Shapiro-Wilk test $p > 0.05$], and the variances were homogenous [Levene's test $p > 0.05$], the effect of bowling delivery type (bouncer, stock or yorker) seen in each estimated parameter (kinematic and kinetic) were assessed using a one-way repeated measures analysis of variance (ANOVA). Where the main effect of bowling delivery type was significant ($p < 0.05$), the post hoc Tukey test was used to compare specific variations. The mean difference between conditions (and its 95% confidence interval) was reported as an unstandardized effect size in meaningful units.

A stepwise linear regression analysis was performed to address the main aim of the study which was to find out the predictive parameters for ball release parameters (ball release height as a percentage of standing height, ball release angle) among the different pitch length conditions. Thoracic angle, shoulder angle and wrist angle parameters were put forward as candidate parameters, as they indicated significant differences between the length conditions. All these joint angles were then included in the analysis and was investigated in different perspectives to find out the cause for the ball release angle and ball release height percentage change.

Time history analysis (continuous analysis) of the joint angles, ground reaction forces and joint moments were performed through statistical parametric mapping (SPM1D.org) in MATLAB to investigate the differences between the deliveries. As with the discrete value analyses, a (statistical parametric mapping) one-way repeated measures ANOVA was used. Statistical parametric mapping paired samples t-tests were used for post-hoc comparisons.

4.7 Chapter summary

The 18-segment full-body inverse dynamics analysis was explained in this chapter, along with how each segment was defined. Details on the interpretation of the output parameters were explained, along with an explanation of how the subject-specific segmental parameters were integrated into the study. The calculations used to determine descriptive variables for each trial were explained. Additionally, details about the statistical techniques employed to produce the results presented in the following chapters were explained.

CHAPTER 5

A COMPARISON OF HOW WELL FAST BOWLERS CAN CONTROL THE LENGTH OF DELIVERY DEPENDING ON THE BOWLING VARIATION

5.1 Abstract

Cricket fast bowling biomechanics has been studied from both an injury and performance perspective in previous investigations, with ball speed the most commonly used performance characteristic. These studies have identified individual aspects of the bowling action linked to ball release speed. However, the evolution of shorter formats of the game has changed fast bowling strategies, with bowling variations such as varying bowling length being commonly used. The aim of this study was to identify how well fast bowlers can control the length of three common deliveries; stock, bouncer and yorker. Data were collected from twenty-one county level fast bowlers where each performed forty-eight deliveries (twenty-four stock, twelve bouncers and twelve yorkers). An eighteen camera Vicon motion analysis system (250 Hz) was used to capture all deliveries with the hand marker and two ball markers labelled for each trial. 2D direct linear transformation was used to calculate the pitch length of each trial from rear camera view video recordings. Mean ± standard deviation pitch length for each delivery type were; stock 7.0 ± 3.7 m, bouncers 10.8 ± 1.4 m and, yorkers 3.8 ± 3.3 m showing that bowlers were more consistent when bowling bouncers (98.3% success rate) than stock (46.4% success rate) and yorkers (24.8% success rate). This study motivates the need for a deeper analysis of kinematics among the different length variations in cricket fast bowling.

5.2 Introduction

Fast bowling has been a major area of study in cricket for more than three decades (Elliott et al., 1986; Burden and Bartlett, 1990b; Portus et al., 2004; Alway et al., 2020). Although fast bowling performance is a very broad field, most of the studies have targeted ball release speed as the performance characteristic (Worthington, 2013; Elliott et al., 1986). Kinematic (Bartlett et al.,1996) and kinetic changes which allow bowlers to produce the maximum release speed have been the major research topic in those investigations.

Most of the studies tend to investigate cricket fast bowling step by step in a sequence starting with the run-up phase. Run up speed is a major factor in producing the initial momentum as it is needed to produce a higher linear velocity (Elliot and Foster, 1989). Although bowlers with faster run-ups have been shown to bowl faster on average, there is likely an optimum run-up speed for any given individual beyond which control and/or ball release speed will decrease (Ferdinands, 2008).

Back foot contact to ball release (see chapter 2) is the most important phase in identifying different techniques and recognising both kinetic and kinematic changes.

Action types (front on, semi on, side on and mixed) are mainly identified on the pelvis-shoulder separation angle and shoulder counter rotation (see Chapter 2). And different characteristics were needed to deliver the ball faster for the different action types. However, bowlers with the maximum separation angle during the delivery stride had a positive correlation with the ball release speed (Portus et al., 2004).

Front foot knee angle has been a main contributor towards the ball release speed and a more extended knee will produce faster deliveries (Burden and bartlett, 1990b; Portus et al., 2004).

Although ball release speed is the main performance characteristic in fast bowling, due to the modern-day arrangements of cricket, ball pitch length and variations play a role in deceiving the batsmen as well. There have not been many studies identifying the kinetic and kinematic changes during the bowling sequence when bowling different length deliveries compared to the number on ball release speed or injury patterns.

Ball pitch length variations might lead the batter to unsettle or mishit the ball which would eventually result in a wicket. In this study three main pitch length variations (yorker, stock ball and bouncer) were investigated. This study intends to identify how well the bowlers can change their length according to their intentions.

5.3 Methods

Twenty-one county playing male fast bowlers (mean ± standard deviation: age 19 ± 2.2 years, height 1.87 ± 0.05 m, mass 81.4 ± 9.7 kg) participated in this investigation. Each bowler was asked to bowl forty-eight full length run up deliveries consisting of twelve bouncer balls, twelve yorker balls, for right-handed batsmen and twelve stock balls for left-handed batsmen.

For the used equipment and the data collection methods see Chapter 3.

5.4 Data processing

All recorded data were manually labelled using Vicon Nexus software (version 2.10) and the hand marker gaps were filled using the "Pattern fill" function within Vicon's Bodybuilder software as the other markers were not used in this study. Marker trajectories (except the ball marker) were filtered using a fourth order lower pass Butterworth filter with a cut off frequency of 20 Hz which was decided after performing a residual analysis (Winter, 1990).

The key instances were manually identified using the motions of the markers; back foot contact was identified using the sudden change of the orientation of MTP markers of the back foot, front foot contact was identified with the help of the force platform (when ground reaction force exceeded 25 N (Worthington, King and Ranson, 2013)). The instance of the ball release was identified by the distance between the ball and hand markers, if the distance increased by more than 20 mm in consecutive frames, it was considered as the ball release instance (Worthington, 2010).

Calculating ball pitch length

2D direct linear transformation was used to calculate the pitch length of trials (Chen, 1994). The rear camera view was used to capture and calculate the ball pitch position. The specific image where the ball was in contact with the pitch was digitised using Silicon Coach software (Live version) to give the ball pitch position in global coordinates of the cricket pitch.

Constant acceleration equations of motion were also used to predict the pitch length with the 3D kinematic data from VICON motion analysis system for the ball as input.

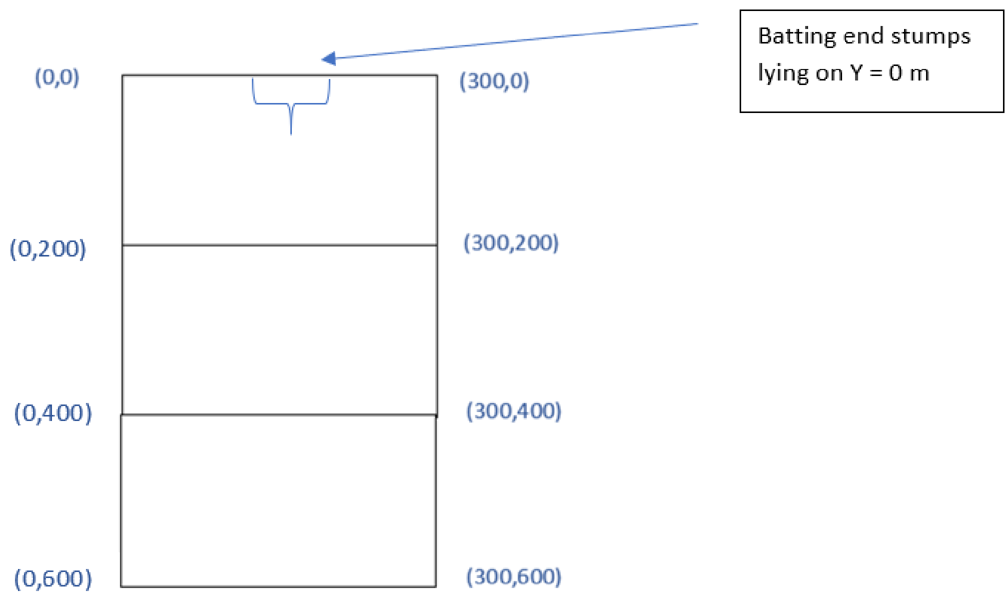


Figure 5.1: Eight digitised points in the 2D image plan coordinate system in the Ball pitch analysis.

Statistical analysis

Statistical analysis was performed within the Statistical Package for the Social Sciences (SPSS v 25.0). Ball pitch length data were normally distributed [Shapiro-Wilk test $p > 0.05$ (0.001 – 0.33)], and the variances were homogenous [Levene's test $p > 0.05$ (0.001)]. Therefore, the effect of bowling delivery type (stock, bouncer or yorker) on pitch length was assessed using a one-way repeated measures analysis of variance (ANOVA). Where the main effect of bowling delivery type was significant ($p < 0.05$), the post hoc Tukey test was used to compare specific variations. The mean difference between conditions (and its 95% confidence interval) was reported as an unstandardized effect size in meaningful units (m), alongside the standard error.

5.5 Results

Out of the 21 bowlers in the study; one of them had a side on shoulder alignment (Portus et al., 2004), seven of them were front on and eight of them were classified as semi on or mid-way. In addition to that five of them were found to be mixing both front on and semi on action. Each bowling delivery type (stock, bouncer and yorker) had over 230 useable trials (Table 5.1).

Table 5.1: Details of actual ball pitch length (relative to the stumps at the batting end) for each delivery type by all participants

delivery type	N	95% confidence interval (m)	max – min (range) (m)	mean ± std (m)
yorker	234	3.4 – 4.2	10.82 – (-13.22)	3.8 ± 3.3
bouncer	236	10.6 – 11.05	14.56 – 5.65	10.8 ± 1.4
stock	237	6.7 – 7.3	11.62 - (-1.90)	7.0 ± 3.7

Bouncer trials showed an ideal mean and a standard deviation value which was 10.8 ± 1.4 m (Table 5.1; Figure 5.6). The mean for the yorker and stock length deliveries was not in the expected area and the standard deviation was over 3 m which is a relatively large margin of error compared to the bouncer balls condition.

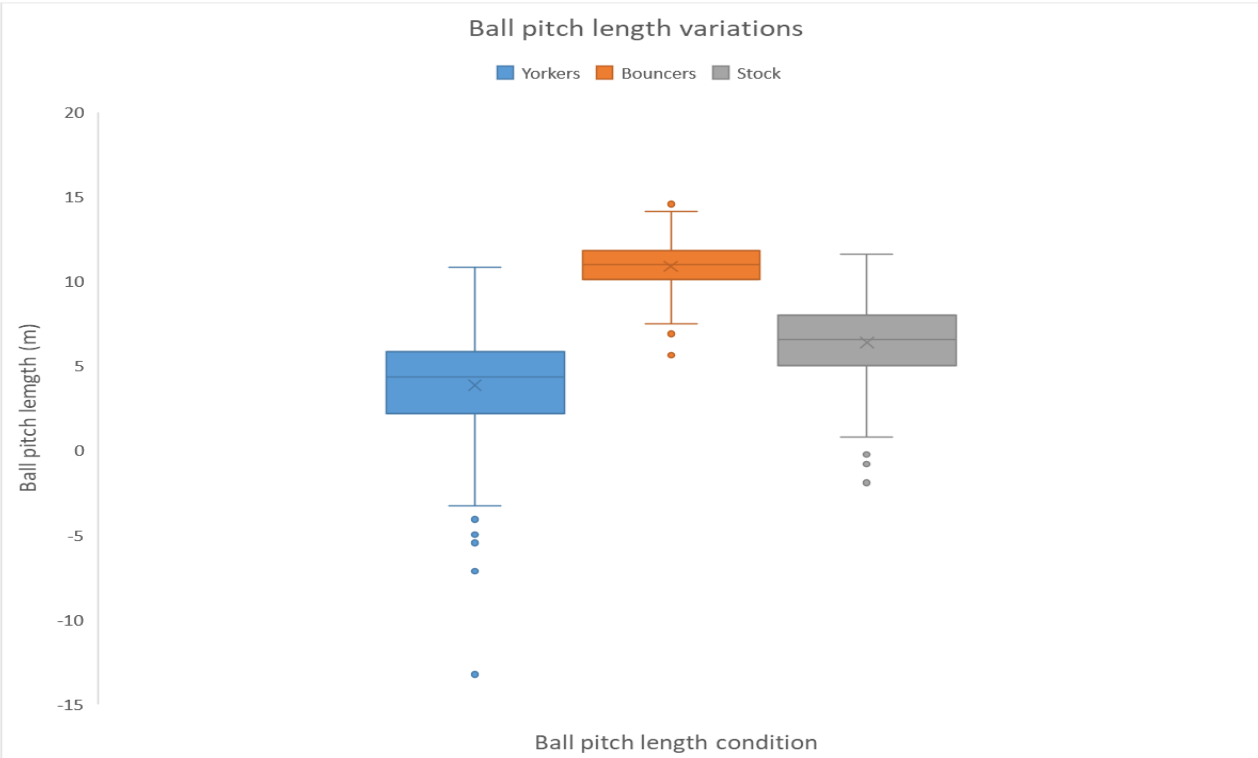


Figure 5.2: An illustration of ball pitch lengths in each group (bouncer, yorker and stock balls).

The mean and standard deviation for each of the three intended lengths clearly shows (Table 5.1; Figure 5.6) that the bowlers in this study struggled to repeatedly bowler stock and yorker deliveries.

Table 5.2: Number of successful trials (in terms of expected pitch length) for each pitch length delivery type

delivery type	total trials (balls)	successful trials (balls)	successful %
yorker	234	58	24.8%
bouncer	236	233	98.7%
stock	237	110	46.4%

(target pitch lengths were considered: 0-2 m yorker, 4-7 m stock, 7+ m bouncer)

The following tables show the means and standard deviations among the ball pitch length conditions in each bowler. Specifically, the yorker length condition had a greater range compared to the other groups for most of the bowlers. Six bowlers had a mean yorker length of over 5 m which is over 2 m from the expected targeted area.

Table 5.3: Details of pitch length for different length balls for all participants

bowler	mean ±std (yorker) (m)	mean ±std (bouncers) (m)	mean ±std (stock) (m)
01	3.33 ± 3.87	11.22 ± 1.36	5.41 ± 1.96
02	3.63 ± 2.51	10.19 ± 1.29	4.83 ± 2.18
03	2.83 ± 2.59	11.44 ± .87	7.69 ± 1.97
04	3.81 ± 2.07	10.46 ± 1.10	6.52 ± 2.04
05	2.39 ± 2.87	9.94 ± 1.68	5.68 ± 2.59
06	2.59 ± 2.73	10.20 ± 1.14	3.98 ± 1.88
07	5.70 ± 1.68	11.97 ± .78	7.35 ± 1.25
08	6.01 ± 2.10	10.73 ± 2.05	6.37 ± 2.15
09	4.01 ± 1.87	11.60 ± 0.89	6.75 ± 1.27
10	3.84 ± 2.20	10.97 ± 1.31	6.83 ± 2.96
11	1.91 ± 3.35	10.91 ± 1.19	6.44 ± 2.40
12	0.73 ± 2.03	11.46 ± 0.88	6.63 ± 1.96
13	3.23 ± 2.33	11.51 ± 0.90	6.61 ± 2.19
14	5.10 ± 1.69	10.83 ± 0.72	6.75 ± 1.29
15	5.11 ± 0.77	11.94 ± 0.82	7.33 ± 1.48
16	-.05 ± 6.44	10.57 ± 1.78	4.74 ± 1.88
17	3.32 ± 3.40	10.20 ± 1.57	5.86 ± 1.21
18	6.76 ± 4.52	10.92 ± 2.05	8.15 ± 2.47
19	2.88 ± 4.04	10.89 ± 1.55	6.87 ± 1.54
20	4.52 ± 1.70	10.53 ± 1.58	6.55 ± 1.82
21	5.98 ± 3.11	9.98 ± 1.83	6.70 ± 2.28

Theoretical explanation

In order to understand the results for the three intended pitch lengths a simple theoretical model was used based upon projectile motion with data from this study used as input. To calculate a pitch length the release conditions for the ball were required for both position (release height and horizontal location) and velocity (vertical and horizontal velocity of the ball).

The time from front foot contact to ball release was calculated for each trial. The mean and standard deviation in terms of time from front foot contact to ball release was then calculated for each bowling length and the trial closest to the median time for each length was selected as representative for that length.

For the three selected trials the (y, z) coordinates of the ball for 11 frames prior to ball release were fitted with a quadratic function of time. The resulting six functions (y (horizontal; z vertical and yorker, bouncer and stock deliveries) were then used to calculate the ball location and velocity for +/- 1 SD for each delivery length,

The resulting ball positions and velocities were then input to the theoretical model to calculate the resulting pitch length for a +/- 1 SD in time (Table 5.5).

Table 5.4: Horizontal ranges among the delivery types for +/- 1 SD of time

delivery type	actual release flight time (s)	landing horizontal location (m)	-1 SD flight time (s)	+1 SD flight time (s)	landing location for (m) –1 SD	landing location (m) +1 SD	range between -1 & +1 SD (m)
yorker	0.470	15.40	0.610	18.73	0.370	13.05	5.68
bouncer	0.201	7.43	0.312	10.06	0.141	6.09	3.97
stock	0.498	16.23	0.613	18.55	0.408	14.34	4.21

The above calculations and theoretical analysis showed that yorkers are most sensitive to perturbations in release time with a 5.68 m range in landing location for a +/- 1 SD in release time (0.005 s). While bouncers were least sensitive with 3.97 m in landing location. In the game of cricket, the margin for pitching a yorker is more critical as a small change in pitch length can result in an 'easy' ball for the batter to put away as rather than being an effective yorker the ball becomes a 'half volley' for the batter to hit. For a bouncer the margins are not so important as pitching shorter does not necessarily make it easier for the batter (any ball pitching more than 7 m from the batter is considered a bouncer).

5.6 Discussion

Most of the previous studies on cricket fast bowling biomechanics were looking into fast bowling speed as their only performance parameter. The intention of this study was to find out the variations in bowling different length trials. This chapter initiates how well the bowlers have succeeded in their tasks. Baseball pitching is another activity where pitching in the correct area is a major performance characteristic, and previous studies have revealed that professional or high school players do not show any significant error differences in fast and break ball pitches (Kawamura et al., 2017). Although fast ball and break ball are considered as pitching variations, this is very much different from fast bowling as the pitching length remains the same in baseball.

Although the participants were recognised as premier fast bowlers in the domestic circuit, the results show the difficulty in performing bowling delivery types. Yorker length was the hardest to land correctly as the mean 3.8 m was 1.8 m shorter than the shortest 'perfect' yorker length of 2 m and the 3.3 m standard deviation shows the difficulty in repeating the same delivery type for several repetitions. The success rate was 24.8% where the intended length converted in between 0 – 2 m.

Furthermore, the stock ball delivery type was also hard to land in the expected area. The mean was 7 m, which is counted as a stock ball, but it is the shortest that a stock could be. The 3.7 m standard deviation again shows the inability of the bowlers in this study to repeated bowl the right length, However, the success rate of 46.4% was much higher than for the yorker length condition.

The bouncer ball delivery type was successfully completed by all the bowlers, with a 10.8 m mean and 1.4 m standard deviation. Success rate was high at 98.7%. Although bouncer balls were on target, the permitted margin of error for a trial was bigger than the yorker and stock ball groups. Any trial which lands over 7 m from the batting end stumps was counted as a bouncer.

The simple theoretical model supported these findings with the variation in pitch length being largest for yorkers followed by stock deliveries and then bouncers. Adding to this the smaller area for successfully bowling a yorker compared with a bouncer demonstrates the difficulty and also importance of being able to control the length of a delivery well.

5.7 Conclusion

This investigation indicates the difficulty in performing the predetermined variations in terms of pitch length. As mentioned in the introduction chapter this analysis was done to fulfil the first objective which was to identify the ability of bowlers to control pitch length. The results suggest greatest difficulty when bowling a yorker and not being able to repeat the length for 75% of the time, the result could change in a match condition where a physical target can be seen for the bowler. Furthermore, this study leads to a deeper technique analysis among the variations in the following chapters.

CHAPTER 6

THE EFFECT OF INTENDED PITCH LENGTH ON KINEMATIC TECHNIQUE PARAMETERS IN CRICKET FAST BOWLING

6.1 Abstract

Cricket fast bowling biomechanics have been studied for many years, with studies typically targeting ball release speed as the only performance characteristic. Although ball release speed is still a major factor, different fast bowling variations have also reduced batting performances. The aim of this study was to identify the main differences in release parameters between three common pitch length deliveries; yorker, bouncer, stock and to find out which technique parameters explains these differences. Data were collected from twenty-one county level fast bowlers where each performed forty-eight deliveries (twelve yorkers, twelve bouncers and twenty-four stock,). An eighteen camera (MX13) Vicon motion analysis system (250 Hz) was used to capture a fifty-three-marker model specifically developed for fast bowling analysis plus two ball markers were used. 2D direct linear transformation was used to calculate the pitch length of each trial from video recordings from a rear camera view placed at the back of the run up starting position. In the study the statistical analysis (ANOVA) revealed significant differences in ball release angle and ball release height among three different delivery types, which led the study to conduct two separate regression analyses to find predictor variables for these parameters in each of the three conditions. Wrist angle, thoracic angle, 2D hand orientation and the 2D thoracic segment orientation were found to be the most decisive predictor technique parameters in each of the conditions which changes the ball path after release.

6.2 Introduction

Cricket generally has three major skills which are bowling, batting, and fielding. Bowling is classified in to two broad categories, namely fast bowling, and spin bowling which is again classified into many other categories such as fast medium, slow medium, swing bowling etc. As the main performance characteristic is the release speed in fast bowling, most of studies have been conducted with the idea of finding out the kinematic and kinetic factors, by dividing the fast-bowling action into a sequence of key phases (Davis and Blanksby, 1976b; Elliott et al., 1986; Burden and Bartlett, 1990a; Portus et al., 2004).

The game of cricket has evolved in a number of different ways in modern day, where shorter formats provide fans with fast paced sporting entertainment (Gulati et al., 2021). Improvements in training facilities and infrastructure have enabled the batters to prepare for higher release speeds from the bowler in the training nets. Furthermore, the batters have started to use more predetermined shots if they can predict the length that the bowler is going to bowl.

The possibility exists for bowlers to bowl more variations to deceive the batter, hoping for a mishit which will ultimately result in a wicket. Although there are studies on spin bowling variations, fast bowling variations were investigated only in few studies. Sarpeshkar et al. (2017) described a reduced performance of batters against in swinging and out swinging balls. Furthermore, EMG activities of muscles acting about the shoulder and wrist have been investigated and a significantly lower root mean square value was identified for Yorkers than bouncer deliveries (Hazari, 2015). This means that different muscles are active in variety of intensities when delivering different variations in fast bowling. This can lead up to different techniques and joint kinematics during the fast-bowling activity. However, studies on variations are less frequent.

Fast bowling studies generally divide the activity into key phases starting from the run up. This run up varies from bowler to bowler as the ultimate target is to gain momentum and transfer it to the ball at the end of the action. The aim of this study is to compare technique (kinematic) parameters among three different pitch length variations which causes the changes in release parameters. As the main part of the bowling sequence, the study will investigate from back foot contact instance to the ball release instance. Ball pitch lengths will be classified in to three main conditions; Yorker, bouncer and stock (see Figure 6.1). Joint angles, 2D segment orientations and joint flexions from back foot contact to ball release phase will be the main kinematic technique parameters which will be investigated as predictors of the changes in release parameters.

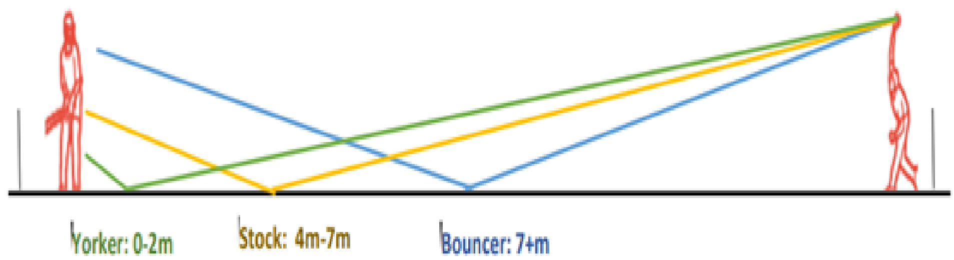


Figure 6.1: An illustration of different ball pitch lengths.

6.3 Methods

21 elite male fast bowlers (mean ± standard deviation: height 1.87 ± 0.05 m, mass 81.4 ± 9.7 kg) participated in this investigation. All the bowlers were identified as 'fast bowlers' by MCCU and county academy fast bowling coaches and were cleared fit to bowl. Testing procedures were explained to each participant individually in accordance with the Loughborough university ethical guidelines and player consents were signed by each player prior to data collection.

For the equipment used and the data collection methods see Chapter 3.

6.4 Data processing

Each trial was reconstructed and labelled using the VICON Nexus (Version 2.10) software. All recorded data were manually labelled using Vicon Nexus software (version 2.10) and gaps were filled using the "Pattern fill" function within Vicon's Bodybuilder software for most of the occasions. The "Rigid body fill" function was also used for filling the gaps if the gap was from a marker in the Head region or a marker from the pelvis area. Only pelvis and head segments were filled using this specific gap filling method as it requires three other markers moving closely and together to calculate the missing marker. In each gap filling occasion, the filled data were visually inspected.

All marker trajectories (except the ball marker) were filtered using a fourth order low pass Butterworth filter with a cut off frequency of 20 Hz which was decided after performing a residual analysis (Winter, 1990).

Key instances were identified and defined as follows. Back foot contact was identified using the sudden change of the orientation of MTP markers of the back foot. Front foot contact was identified with the help of the force platform (when ground reaction force exceeded 25 N (Worthington, King and Ranson, 2013)). Ball release instance was identified after observing the time history of the distance between the ball and hand marker. If the distance between the two markers exceeded the previous frame by 20 mm, it was considered as the ball release (Worthington, King and Ranson, 2013).

For 2D Direct Linear Transformation, marker model, calculation of COM and joint angles see Chapter 4.

<u>Statistical analysis</u>

Statistical analyses were performed within the Statistical Package for the Social Sciences (SPSS v 25.0). As the release parameter data were normally distributed [Shapiro-Wilk test $p > 0.05$ (0.09 – 0.94)], and the variances were homogenous [Levene's test $p > 0.05$ (0.09 – 0.75)], the effect of bowling delivery type (bouncer, yorker or stock) on release parameters were assessed using a one-way repeated measures analysis of variance (ANOVA). Bowling variation categories were defined according to the intended delivery, regardless of their actual outcome. Where the main effect of bowling delivery type was significant ($p < 0.05$), the post hoc Tukey test was used to compare specific variations. The mean difference between conditions (and its 95% confidence interval) was reported as an unstandardized effect size in meaningful units.

The study then investigated the technique parameters at ball release that best explain differences in ball release angle and relative ball release height, which were the main ball specific results from the analysis above for all three conditions separately. Therefore, a Pearson correlation analysis and a stepwise linear regression analysis was performed to address the main aim of the study which was to find out the predictive parameters for ball release parameters (ball release height as a percentage of standing height, ball release angle) among the different pitch length conditions. The regression analysis assumes the relationship between these predictive factors as independent of the person performing the bowling as only one trial from each player were included in one regression analysis.

Thoracic angle, shoulder angle and wrist angle parameters were put forward as candidate parameters, as they indicated significant differences between the length conditions (Table 6.1). All these joint angles were then included in the analysis to predict the ball release angle and ball release height percentage change.

Each of these candidate variables were analyzed in the following aspects;

1) Joint angle at ball release
2) Joint flexion/extension from front foot contact to ball release
3) 2D segment orientation at ball release

In addition, 2D finger orientation at ball release (Figure 6.5) was also calculated and used in the regression models as it represents the ball position just before the ball release instance.

2D finger orientation at ball release

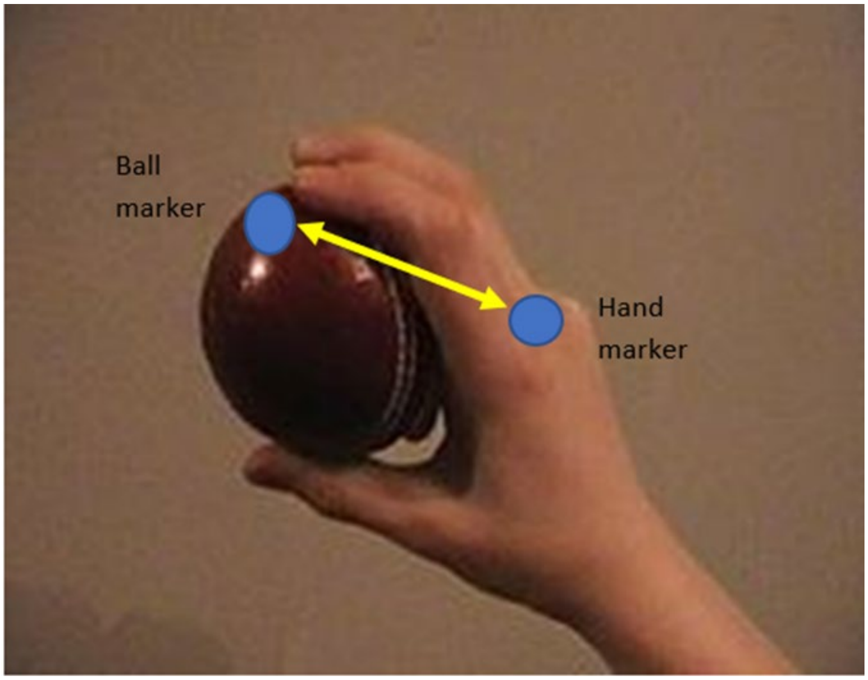


Figure 6.2: Ball and hand markers which was used to calculate the 2D finger orientation at the point of ball release.

2D finger orientation was calculated using the marker of the ball and the hand marker. The imaginary line between the two markers in reference to the global horizontal y axis was calculated for this purpose.

Among these technique parameters, 2D finger orientation at ball release revealed a higher proportion of variance associated eta squared value ($\eta 2$ = 0.31) than other parameters among the different pitch length conditions in the one-way repeated measures ANOVA.

The requirement for the inclusion of a parameter in the regression equations was $p < 0.05$. The percentage of variance in the dependent variable (ball release height as a percentage of standing height, ball release angle) explained by the independent variable (s) in a regression was determined by Wherry's (1931) adjusted R^2 -value.

6.6 Results

Table 6.1: Descriptives, significance and effect sizes of the kinematic parameters between intended bowling delivery types

parameter	yorker Mean ± Std) (95% CI)	bouncer Mean ± Std (95% CI)	stock Mean ± Std (95% CI)	ANOVA P value (multiple comparisons)	Eta squared value η^2
Ball speed (Resultant) (ms^{-1})	31.5 ± 2.3 (30.9 -32.1)	33.1 ± 2.2 (32.8 - 33.3)	32.1 ± 1.9 (31.7 - 32.5)	< 0.001 (A, C)	0.08
Ball speed (Vertical) (ms^{-1})	1.2 ± 0.5 (1.1 - 1.4)	7.4 ± 1.6 (7.2 - 7.6)	3.0 ± 0.8 (2.9 - 3.2)	< 0.001 (A, B, C)	0.77
Ball speed (Horizontal) (ms^{-1})	31.4 ± 2.2 (30.8 - 32.0)	32.1 ± 2.2 (31.9 - 32.4)	31.9 ± 1.9 (31.6 - 32.3)	0.07	
Ball release angle (°)	2.2 ± 0.9 (2.0 - 2.5)	13.0 ± 2.7 (12.6 - 13.3)	5.4 ± 1.2 (5.1 - 5.6)	< 0.001 (A, B, C)	0.78
Ball release height percentage	112.3 ± 4.0 (111.2 - 113.4)	107.4 ± 4.0 (106.9 - 107.9)	111.3 ± 3.9 (110.6 - 112.1)	< 0.001 (A, C)	0.22
Front foot Knee angle (BR) (°)	153.6 ± 24.6 (146.7 - 160.5)	156.8 ± 22.8 (153.8 - 159.8)	152.9 ± 21.8 (148.6 - 157.3)	0.315	
Thoracic angle (BR) (°)	152.1 ± 10.5 (149.2 -154.9)	148.2 ± 10.5 (146.8 - 149.5)	150.1 ± 11.4 (147.9 - 152.3)	0.035 (A)	0.02
Shoulder angle (BR) (°)	-147.9 ± 21.4	-150.3 ± 19.1	-148.8 ± 19.8	0.124	

***A denotes significant difference between Yorker and Bouncer conditions**

*** B denotes significant difference between Yorker and Stock conditions**

*** C denotes significant difference between Stock and Bouncer conditions**

*** FFC is abbreviated for front foot contact * BR**

	(-154.0 – (-141.7)	(-152.9 – (-147.7))	(-152.9 – (-144.7))			**is abbreviated for ball release instance**
Wrist angle (BR) (°)	192.6 ± 8.0 (190.5 - 194.8)	188.6 ± 7.9 (187.5 - 189.6)	191.9 ± 10.6 (189.7 - 194.0)	< 0.001 (A, C)	0.02	
2D Shoulder orientation (BR) (°)	21.5 ± 8.0 (19.2 - 23.7)	28.4 ± 8.1 (27.3 - 29.5)	20.9 ± 6.5 (19.6 - 22.2)	< 0.001 (A, C)	0.14	
2D hand orientation (BR) (°)	-13.7 ± 10.8 ((-16.6) - (-10.7))	2.1 ± 14.5 ((-0.25) - 4.0)	-10.1 ± 11.6 ((-12.3) – (-7.9))	< 0.001 (A, C)	0.17	
2D thoracic orientation (BR) (°)	36.8 ± 17.2 (32.1 – 41.6)	31.2 ± 14.6 (29.3 – 33.1)	36.8 ± 13.4 (34.2 – 39.3)	0.003 (A, C)	0.04	
Shoulder flexion (FFC- BR) (°)	135.0 ± 37.4 (124.2 – 145.7)	132.9 ± 40.0 (127.5 – 138.3)	126.2 ± 42.6 (117.5 – 134.9)	0.882		
Wrist flexion (FFC – BR) (°)	31.0 ± 16.0 (26.6 – 35.4)	24.7 ± 18.7 (22.2 – 27.1)	25.6 ± 18.0 (22.0 – 29.2)	0.027 (A, B)	0.02	
Thoracic flexion (FFC- BR) (°)	27.7 ± 6.7 (25.8 – 29.7)	31.2 ± 7.0 (30.3 – 32.1)	29.6 ± 7.7 (28.1 – 31.1)	0.001 (A, C)	0.05	
Delivery stride length %	81.8± 6.6 (79.9 - 83.6)	80.5 ± 6.7 (79.6 - 81.3)	80.3 ± 6.3 (79.0 - 81.5)	0.363		
2D finger orientation (°)	58.4 ± 9.3 (55.9 – 60.9)	42.0 ± 9.1 (40.9 – 43.2)	52.0 ± 9.1 (50.3 – 53.8)	< 0.001 (A, B, C)	0.31	

As shown in Table 6.1, the largest eta squared effect size ($\eta^2 = 0.78$) was for the ball release angle, which had significant differences among ball pitch length variations ($p < 0.001$). Bouncer balls had the greatest mean value in ball release angle relative to the horizontal line (mean ± SD: 13.0 ± 2.7°) compared to stock balls (5.4 ± 1.2°) and yorkers (1.9 ± 1.8°) (Figure 6.3). Furthermore, it is the only ball-specific (post-release) kinematic parameter which shows significant differences in all pairwise comparisons ($p < 0.001$). Similarly, ball release height as a percentage of standing height showed significant differences between all length conditions ($p < 0.001$) and a large main effect size ($\eta^2 = 0.22$). The resultant ball release speed also showed significant differences with a medium effect size (η^2 0.08). Although there is a significant main effect for resultant ball speed on the delivery type ($p < 0.05$), the post-hoc tests showed only that bouncers (33.1 ± 2.2 ms^{-1}) are significantly different to stock (32.1 ± 1.9 ms^{-1}) and yorker length (31.5 ± 2.3 ms^{-1}) conditions.

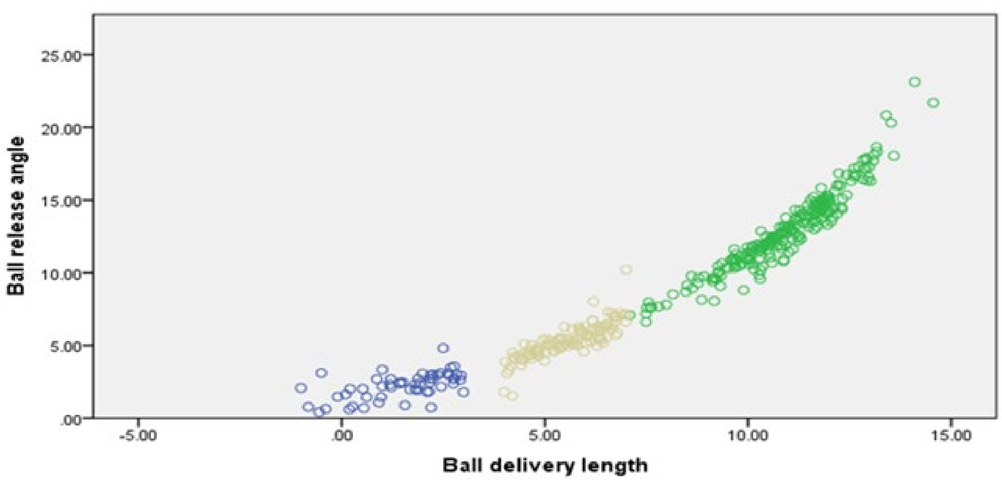


Figure 6.3: Ball release angles at different pitch lengths: yorker (blue), stock (yellow), and bouncer (green).

Furthermore, in order to compare among the three delivery types, two separate regressions were done for each delivery type to find out the technique parameters which can predict the change of ball release height percentage and ball release angle. Altogether there were six regressions, as detailed below.

1) Regression to predict the ball release angle for yorker balls
2) Regression to predict the ball release angle for bouncer balls
3) Regression to predict the ball release angle for stock balls
4) Regression to predict the ball release height percentage for yorker balls
5) Regression to predict the ball release height percentage for bouncer balls
6) Regression to predict the ball release height percentage for stock balls

1) <u>Ball release angle for yorker balls</u>

Twenty-one trials were selected, using one yorker trial from each of the twenty-one fast bowlers. Each included representative trial was selected individually as the one which was closest to the mean of the successful trials which landed in the ball pitch length range for that delivery type.

Table 6.2: Details of the predictive equations using stepwise regression method to explain ball release angle for yorker balls

model	kinematic parameter	coefficient value (r)	95% CI (unstandardized coefficient) (r)	P value	explained percentage (95% CI)
1	(Constant)	-16.00	-20.8 – (-11.1)	<.001	75.3% (<1% - 98%)
	Wrist angle at BR	0.097	0.07 – 0.123	<.001	
2	(Constant)	-9.964	-14.69 –(-5.23)	<.001	86.6% (<1% - 97%)
	Wrist angle at BR	0.069	0.045– 0.093	<.001	
	2D hand orientation at BR	0.063	0.031 - 0.096	.001	

* FFC is abbreviated for front foot contact * BR is abbreviated for ball release instance * CI abbreviated for confidence intervals

The results of stepwise regression analysis (Table 6.2) suggest that 75.3% of variation in ball release angle can be explained using two kinematic parameters. The best individual predictor was the wrist angle at ball release, which alone explained 75.3% of the variation. As the wrist angle is getting higher, a more extended wrist is produced at the ball release it predicts the ball release angle. The percentage of variation explained increases to 86.6% when 2D hand orientation is also included within the predictive model.

2) <u>Ball release angle for bouncer balls</u>

Twenty-one trials were selected using one bouncer trial from each of the twenty-one fast bowlers. Each included representative trial was selected individually as the one which was closest to the mean of the successful trials which landed in the ball pitch length range for that delivery type.

Unexpectedly, there were no technique parameter having significant correlations with ball release angle. Therefore, it was concluded that no clear technique parameter was found to be the predictor variable for the ball release angle change in bouncer balls.

3) Ball release angle for stock balls

Twenty-one trials were selected using one stock ball trial from each of the twenty-one fast bowlers. Each included representative trial was selected individually as the one which was closest to the mean of the successful trials which landed in the ball pitch length range for that delivery type.

Table 6.3: Details of the predictive equations using stepwise regression method to explain ball release angle for stock balls

model	kinematic parameter	coefficient value (r)	95% CI (unstandardized coefficient) (r)	P value	explained percentage (95% CI)
1	(Constant)	5.70	5.02 – 6.38	<.001	31.2% (<1% - 98%)
	2D hand orientation at BR	0.047	0.13 – 0.08	<.05	

* FFC is abbreviated for front foot contact * BR is abbreviated for ball release instance * CI abbreviated for confidence intervals

The results of stepwise regression analysis (Table 6.3) suggest that only 31.2% of variation in ball release angle can be explained using one kinematic parameter for the stock balls. The best and only individual predictor was the 2D hand orientation at ball release.

4) **<u>Ball release height percentage for yorker balls</u>**

Similar to the previous analysis twenty-one trials were selected using one yorker trial from each of the twenty-one fast bowlers. Each included representative trial was selected individually as the one which was closest to the mean of the successful trials which landed in the ball pitch length range for that delivery type.

Table 6.4: Details of the predictive equations using stepwise regression method to explain ball release height percentage for yorker balls

model	kinematic parameter	coefficient value (r)	95% CI (unstandardized coefficient) (r)	P value	explained percentage (95% CI)
1	(Constant)	80.52	60.8 – 100.1	<.001	38.2% (<1% - 98%)
	Thoracic angle at BR	0.206	0.07 – 0.33	<.05	
2	(Constant)	83.82	66.7 – 100.8	<.001	55.2.% (<1% - 97%)
	Thoracic angle at BR	0.155	0.037– 0.273	<.05	
	2D thoracic segment orientation at BR	0.122	0.024 - 0.221	.005	

* FFC is abbreviated for front foot contact * BR is abbreviated for ball release instance * CI abbreviated for confidence intervals

The results of stepwise regression analysis (Table 6.4) suggest that 55.2% of variation in ball release height percentage can be explained using two kinematic parameters. The best individual predictor was the thoracic angle at ball release, which alone explained 38.2% of the variation. The percentage of variation explained increases to 55.2% when 2D thoracic segment orientation was also included within the predictive model.

5) **<u>Ball release height percentage for bouncer balls</u>**

Twenty-one trials were selected using one bouncer trial from each of the twenty-one fast bowlers. Each included representative trial was selected individually as the one which was closest to the mean of the successful trials which landed in the ball pitch length range for that delivery type.

Table 6.5: Details of the predictive equations using stepwise regression method to explain ball release height percentage for bouncer balls

model	kinematic parameter	coefficient value (r)	95% CI (unstandardized coefficient) (r)	P value	explained percentage (95% CI)
1	(Constant)	70.63	36.9 – 103.8	<.001	23.3.% (<1% - 98%)
	Wrist angle at BR	0.201	0.024 – 0.378	<.05	
2	(Constant)	53.53	19.4 – 87.69	<.05	39.1.% (<1% - 97%)
	Wrist angle at BR	0.190	0.031– 0.349	<.05	
	2D thoracic segment orientation at BR	0.125	0.004 – 0.247	<.05	
3	(Constant)	55.60	26.62 – 84.59	0.001	56.9% (<1% - 97%)
	wrist angle at BR	0.115	-0.033 – 0.264	<.05	
	thoracic angle at BR	0.207	0.084 – 0.331	<.05	
	2D hand orientation at BR	-0.089	-0.164 – (-0.15)	<.05	
4.	(Constant)	73.37	54.66 – 92.08	<0.001	51.3 % (<1% - 97%)
	Thoracic angle at BR	0.234	0.109 – 0.359	<0.05	
	2D hand orientation at BR	-0.114	-0.185– (-0.043)	<0.05	

* FFC is abbreviated for front foot contact * BR is abbreviated for ball release instance * CI abbreviated for confidence intervals

The results of stepwise regression analysis (Table 6.5) suggest that 56.9% of variation in ball release height percentage can be explained using three kinematic parameters for the bouncer balls. The best individual predictor was the wrist angle at ball release, which alone explained 23.3% of the variation. The percentage of variation explained increases to 56.9% when the thoracic angle and the 2D hand orientation were also included within the predictive model.

6) Ball release height percentage for stock balls

Twenty-one trials were selected using one stock ball trial from each of the twenty-one fast bowlers. Each included representative trial was selected individually as the one which was closest to the mean of the successful trials which landed in the ball pitch length range for that delivery type.

Table 6.6: Details of the predictive equations using stepwise regression method to explain ball release height percentage for stock balls

model	kinematic parameter	coefficient value (r)	95% CI (unstandardized coefficient) (r)	P value	explained percentage (95% CI)
1	(Constant)	106.02	102.8 – 109.24	<.001	49.8% (<1% - 98%)
	2D thoracic segment orientation at BR	0.158	0.079 – 0,238	<.05	
2	(Constant)	91.47	77.542– 105.40	<.001	60.2% (<1% - 98%)
	2D thoracic segment orientation at BR	0.121	0.041 – 0.200	<.05	
	Thoracic angle at BR	0.105	0.007 – 0.204	<.05	

* FFC is abbreviated for front foot contact * BR is abbreviated for ball release instance * CI abbreviated for confidence intervals

The results of stepwise regression analysis (Table 6.6) suggest that up to 60.2% of variation in ball release height percentage can be explained using two kinematic parameters for the stock balls. The best and individual predictor was the 2D thoracic segment orientation at ball release which explained 49.8% alone. The percentage of variation explained raised up to 60.2 % when the thoracic angle at BR was also added to the equation.

Summary of the regressions

As explained earlier in the analysis, six different regressions were done to find out the predictor technique parameters which can explain the differences among the pitch length conditions. The summary is as follows (Table 6.7).

Table 6.7: Summary of the predictive equations using stepwise regression method to explain ball release angle and ball release height percentage

Ball pitch length condition	Ball release angle prediction (predictor variables)	Ball release height percentage prediction (predictor variables)
Yorker balls	Wrist angle at BR 2D hand orientation at BR	Thoracic angle at BR 2D thoracic segment orientation at BR
Bouncer balls	NO correlations	Wrist angle at BR Thoracic angle at BR 2D hand orientation at BR
Stock balls	2D hand orientation at BR	2D thoracic segment orientation at BR Thoracic angle at BR

6.7 Discussion

Cricket fast bowling variations have been effective in reducing batters' performance (Sarpeshkar et al., 2017) and bowlers use more pitch length delivery types (e.g., yorkers and bouncers) specifically in T20 cricket (Justham et al., 2008). This study was intended to find out the major kinematic technique differences within the different pitch length trials which predicts the changes in release parameters. A repeated measures ANOVA was used to find out the key release parameters differing between the three different pitch length deliveries (yorker, bouncer and stock). Furthermore, a linear regression was used to find out the key kinematic technique parameters which predicts those release parameters.

The ANOVA revealed significance differences between the three pitch length delivery types for all ball-specific parameters at ball release (release speed, release angle, relative release height). As ball release angle (η^2= 0.78) and release height (η^2= 0.22) showed high and moderate effect sizes, the main technique factors associated with changes in these ball-specific parameters were investigated. Furthermore, among the joint angles, knee flexion had no significant effect on ball pitch length. Although front knee flexion was described as mainly correlated with ball release speed in a previous study (Worthington et al., 2013), it was not a decisive factor in pitch length variations. Moreover, thoracic flexion at ball release, wrist flexion at ball release, and 2D global orientation of hand revealed significant differences between pitch length conditions.

2D finger orientation was calculated with reference to the global y (horizontal) axis, and lower angles describe the finger moving away from the wrist and creating a higher release angle which produces short pitch length balls. This also showed significant differences between the conditions. Shoulder joint angle was calculated using the humerus segment orientation with reference to the trunk segment and it didn't reveal any significant differences or correlation with ball release angle. This may resemble a robust bowling action which bowlers develop from a young age. The shoulder joint angle which is created at the point of ball release remains not significantly different under different conditions. However, the 2D upper arm orientation revealed significant differences between the conditions in the repeated measures ANOVA ($p < 0.001$). This is mainly due to the shoulder global position which can be affected by the changes of thoracic angle and any other lower body angle in different conditions. A greater thoracic flexion can change the 2D orientation of the shoulder while maintaining the same shoulder joint angle.

In the first regression model which was targeting the ball release angle of yorker balls 86.6% of the variation in ball release angle was explained by wrist angle at ball release and 2D hand orientation at ball release. This explains that when it comes to yorker deliveries the wrist angle (which is more extended than other two conditions) is the most important technique parameter which decides the path of the ball.

In the second regression model, which was targeting the ball release angle of bouncer balls, unexpectedly no technique parameter was correlated with the ball release angle. Therefore, the regression model which explains the ball release angle in bouncer balls was not generated. No correlations in bouncer balls with the release angle could be explained as the release angle range was having higher ranges when comparing to the other pitch length conditions.

In the third regression model which was targeting the ball release angle in stock balls 31.2% of the variation in ball release angle was explained by 2D hand orientation at ball release.

Furthermore, the next regression models were targeting the ball release height percentage of different conditions. The fourth regression model was predicting the ball release height percentage of yorker balls. 55.2% of the variation in ball release height percentage was explained by thoracic angle at ball release and 2D thoracic segment orientation at ball release.

The fifth regression model revealed that 56.9% of the variation in ball release height percentage of the bouncer balls could be explained by three technique parameters. Wrist angle, thoracic angle and 2D hand orientation at ball release were the predictor parameters similar to the regression on yorker balls.

Finally, 60.2% of the variation in ball release height percentage of stock balls were explained by thoracic angle at ball release and 2D thoracic segment orientation at ball release in the sixth regression model. This explains that when it comes to stock deliveries wrist angle and thoracic angle (similar to other variations) are the most important technique parameters which decide the path of the ball.

These regression analysis shows that wrist angle, 2D hand orientation, thoracic angle and 2D thoracic segment orientation were predictor variables in most of the regressions. 2D hand orientation has been a predictor variable for both stock and yorkers which shows the global orientation of upper hand importance in predicting the release angle. In addition the wrist angle was crucial for yorkers as a more extended wrist has helped yorker balls lower release angle at ball release for the ball to have a longer path. Therefore, wrist angle has been chosen as a predictor variable in addition to the 2D hand orientation for the yorkers as well. Thoracic angle and 2D thoracic segment orientation were predictor technique parameters for release height percentage in all pitch length conditions which shows the importance of thoracic angle and the global orientation of the region to get the needed release height in each type of a ball. The three conditions were analysed separately in regressions as the three groups consist of three different type of outcomes (pitch lengths).

A more flexed 2D thoracic segment orientation at ball release leans the body forward and reduces the release height of a bowler. If the thoracic is more extended, higher ball release will be acquired by the ball if all the other parameters are the same. The ANOVA analysis revealed the association of higher ball release heights with yorker deliveries as well. Similar to 2D thoracic segment orientation, the thoracic joint angle was also a good predictor of ball release height as the inclusion of the parameter increased the proportion of variation in each predictive model. This means that a more upright thoracic region in both 2D and 3D at the ball release will result in a higher ball release height.

The results indicate the importance of several key parameters in changing the release parameters which ultimately effects the ball pitch length. Although previous fast bowling studies looked into the EMG activities in shoulder muscles, wrist muscles and biceps brachii (Hazari, 2015; Ali, 2016) and significant changes among the different pitch length conditions were revealed it didn’t explain any technique parameters. Initial expectation was to find significant changes in wrist angle as the bowlers do flex their wrist to gain speed (Sisodia. 2017) and the wrist angle directly affects the release angle. A previous study (Hore et al., 1996a) had already stated the importance of finger mechanics stating the influence of the fingers (specifically by the proximal and distal phalanges) in overarm throws. Moreover, the ball direction was established about the mid-way between hand grip release and finger grip release (Watts et al., 2004). The current study confirms the previous findings as the regression model reveals the importance of the 2D finger orientation at ball release as a one of the key factors which has significant differences among the conditions.

Furthermore, coaches can include these findings in their skill training as finger movements can easily cause pitch length variations. Coaches will be able to train bowlers with a more robust technique with minimum technique changes when they need to perform different pitch length variations.

The regression analysis was done using only one trial from each player for each delivery type. One of the main limitations in the study, as mentioned in Chapter 5, the presence of a visible batter would have improved the ball pitch length figures as more trials could have been used in the regression model.

As mentioned in the introduction this is very much a new aspect of research in fast bowling, as pitch length variations have not been studied with the intention of finding the kinematic technique changes. Future studies can include different action types (front on, side on midway and mixed) (Portus et al., 2004) as the action type was not considered in the analysis. The changes in the orientation of shoulder – pelvic angles at back foot and front foot could identify different kinematic parameters as the most decisive for different actions.

6.8 Conclusion

In conclusion, this chapter provides an understanding of the technique parameters most associated with different length deliveries in cricket fast bowling (second major objective in the overall study). The study identifies ball release angle and release height as a percentage of standing height as the decisive release parameters. Release height percentage and the ball release angle were largely associated with the orientation of the thoracic segment, thoracic joint angle, wrist angle and 2D hand orientation in all three delivery conditions. Ball - finger 2D orientation also showed significant differences among the three conditions. These findings are likely to be very useful in identifying key differences amongst the different pitch lengths for different players during training. Furthermore, this leads to an investigation of a continuous analysis in order to find out exactly where these changes occur during the bowling action.

CHAPTER 7

A CONTINUOUS ANALYSIS OF UPPER BODY JOINT ANGLES FROM BACK FOOT CONTACT TO BALL RELEASE IN DIFFERENT LENGTH CRICKET FAST BOWLING DELIVERIES

7.1 Abstract

Cricket fast bowling is a skill with a sequence of activities done to release the ball faster than spin bowling. Although ball release speed has been the main performance outcome, Different fast bowling variations can also influence batting performance. The aim of this study was to compare kinematic technique parameters of cricket fast bowlers from back foot contact to ball release between three common pitch length deliveries; stock (4 - 7 m), yorker (0 - 2 m), and bouncer (> 7 m). Data were collected from twenty-one county level fast bowlers who each performed thirty-six deliveries (twelve stock, twelve bouncers and twelve yorkers). An eighteen camera (MX13) Vicon motion analysis system (250 Hz) was used to capture the actions, with a fifty-three-marker model specifically developed for fast bowling analysis plus two (tape) ball markers used. Two-dimensional direct linear transformation was used to calculate the pitch length of each trial from rear camera view video recordings. One-dimensional statistical parametric mapping analysis revealed significant differences ($p < 0.003$) between stock balls and both bouncers and yorkers in the first 30% of normalized time duration after back foot contact and a significant difference between bouncers and stock ($p < 0.002$) in the last 20% of normalized time before ball release for the thoracic angle. Furthermore, wrist angle was significantly different ($p < 0.001$) between yorkers and bouncers from back foot contact to ball release, while stock had a significant difference compared to yorkers ($p < 0.04$) up to 90% of normalised time from back foot contact to ball release. Two-dimensional orientations of the upper arm, hand and thoracic segment also showed significant differences in continuous data between conditions.

7.2 Introduction

Cricket fast bowling variations has been studied in fast bowling related studies recently as it has reduced the batter's performance than normal line and length delivery. (Sarpeshkar et al., 2017; Woolmer et al., 2008). Fast bowling variations can be classified depending on the swing, pitch length and the release speed of the ball. In this study different pitch length variations are being investigated in a continuous analysis throughout key phases of the skill.

The fast-bowling skill starts with the run-up phase, where the bowler chooses their suitable running distance to gather momentum before the main phases of the skill (Tyson, 1976). The main phases of the fast-bowling skill start from the back foot contact until the ball release instance. No studies have investigated variations in technique parameters for different pitch length deliveries.

Sarpeshkar et al. (2017) discussed a reduced performance of batters against in swinging and out swinging balls compared to non-swinging balls. Furthermore, muscle excitation around the shoulder and wrist joints, via electromyography, have been compared between yorker and bouncer deliveries and found that yorkers produce higher values in wrists while bouncers produce higher values around shoulders (Hazari, 2015). Callaghan et al. (2021) compared ground reaction forces during front foot contact for different pitch length deliveries and found no significant differences in peak vertical force, peak braking force, or impulses.

The previous chapter identified relative ball release height and ball release angle as the key difference between pitch lengths, as expected in projectile motion activities. Yorker deliveries were associated with higher release heights, while the changes in thoracic angle, shoulder angle and wrist angles at the instants of front foot contact and ball release all contributed to pitch length outcomes.

The aim of the current study was to compare joint angles between fast bowling pitch length conditions throughout the phases from back foot contact to ball release.

7.3 Methodology

21 male fast bowlers (mean ± standard deviation: height 1.87 ± 0.05 m, body mass 81.40 ± 9.74 kg) participated in this investigation. Each bowler was asked to bowl 48 deliveries from a full-length run up. This consisted of 12 bouncer balls, 12 yorker balls, 12 stock balls for right-handed batsmen and 12 stock balls for left-handed batsmen. Only one of either set of twelve stock balls was selected. Some bowlers found it difficult to pitch the ball in the expected 4 - 7m margin when they were bowling to one of the left- or right-handed imaginary batters. Considering this, either of the set of stock balls which was the closest to the expected margin (4-7 m from batting end stumps) was selected for further analysis. These deliveries were bowled in a randomised order.

The following distances from the batting end stumps were considered for the classification of delivery type (i.e., pitch length) as in a previous study (Hazari, 2016):

0 - 2 m: yorker
4 - 7 m: stock ball
> 7 m: bouncer

For the equipment used and the data collection method see Chapter 3.

7.4 Data processing

For the key instances identification, marker model labelling process, calculation of COM and joint angles see Chapter 4 (page 40 – 45).

Furthermore, for each trial, joint angles (wrist, shoulder, lumbar, thoracic, hip, knee) were calculated and time normalised from back foot contact to ball release. Three trials which landed closer to the middle of the expected area in each variation were averaged and used in the discrete and continuous analysis.

7.5 Statistical analysis

Three trials from each player were included in the analysis including one from each variation as they were separate data points unrelated to each other. Discrete time point analyses were performed within the Statistical Package for the Social Sciences (SPSS v 25.0). A one-way repeated measures analysis of variance (ANOVA) compared joint angles at ball release between the three pitch length conditions. Where significant ($p < 0.05$) main effects were reported, post hoc tukey test statistics compared individual conditions. Continuous analyses of the time normalized joint angles were performed through statistical parametric mapping (SPM1D.org) one-way repeated measures ANOVAs in MATLAB to investigate the differences between the deliveries. Similar to the discrete analysis, where significant ($p < 0.05$) main effects were reported, post hoc tukey test was used to compare individual conditions.

7.6 Results

The ball release parameters (release speed, release angle, relative release height percentage) showed significant differences ($p < 0.05$) between the three-pitch length conditions (Table 7.1). There were also significant differences in wrist angle at ball release between Yorkers and both bouncers and stock trials.

Table 7.1: Descriptive and inferential statistics for kinematic parameters at ball release

parameter	yorker Mean ± SD (95% CI)	bouncer Mean ± SD (95% CI)	stock Mean ± SD (95% CI)	ANOVA *p*-value (post hoc tukey test)	effect size η^2
Ball speed (Resultant) (ms^{-1})	31.5 ± 2.3 (30.9 -32.1)	33.1 ± 2.2 (32.8 - 33.3)	32.1 ± 1.9 (31.7 - 32.5)	< 0.001 (A, C)	0.08
Ball release angle (°)	2.2 ± 0.9 (2.0 - 2.5)	13.0 ± 2.7 (12.6 - 13.3)	5.4 ± 1.2 (5.1 - 5.6)	< 0.001 (A, B, C)	0.78
Ball release height	112.3 ± 4.0 (111.2 - 113.4)	107.4 ± 4.0 (106.9 - 107.9)	111.3 ± 3.9 (110.6 - 112.1)	< 0.001 (A, C)	0.22
percentage Front foot Knee angle (BR) (°)	153.6 ± 24.6 (146.7 - 160.5)	156.8 ± 22.8 (153.8 - 159.8)	152.9 ± 21.8 (148.6 - 157.3)	0.315	
Thoracic angle (BR) (°)	152.1 ± 10.5 (149.2 -154.9)	148.2 ± 10.5 (146.8 - 149.5)	150.1 ± 11.4 (147.9 - 152.3)	0.035 (A)	0.02
Shoulder angle (BR) (°)	-147.9 ± 21.4 (-154.0 – (-141.7)	-150.3 ± 19.1 (-152.9 – (-147.7))	-148.8 ± 19.8 (-152.9 – (-144.7))	0.124	
Wrist angle (BR) (°)	192.6 ± 8.0 (190.5 - 194.8)	188.6 ± 7.9 (187.5 - 189.6)	191.9 ± 10.6 (189.7 - 194.0)	< 0.001 (A, C)	0.02

* A denotes significant difference between Yorker and Bouncer conditions

* B denotes significant difference between Yorker and Stock conditions

* C denotes significant difference between Stock and Bouncer conditions

* FFC is abbreviated for front foot contact

* BR is abbreviated for ball release instance

1) Back hip flexion angle

The SPM one-way repeated measures ANOVA result didn't reveal any significant differences ($p > 0.05$) in back hip flexion angle from back foot contact to ball release among the three variations (Figure 7.4).

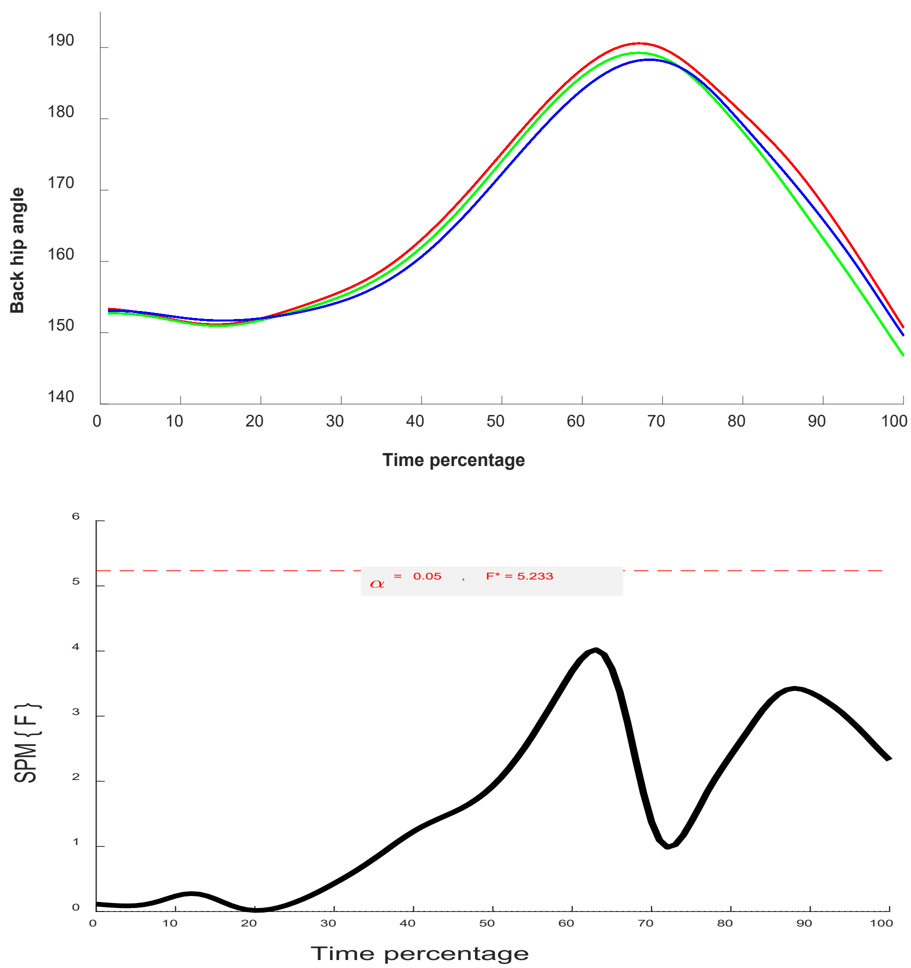


Figure 7.1: Top: Mean time-normalised back hip flexion angle (top) for yorker (red), bouncer (green) and stock (blue) deliveries from back foot contact to ball release. Bottom: Statistical parametric mapping results for the effect of pitch length condition on back hip flexion angle within the one-way repeated measures ANOVA.

2) Back knee flexion angle

The SPM one-way repeated measures ANOVA result didn't reveal any significant differences ($p > 0.05$) in back knee flexion angle from back foot contact to ball release among the three variations (Figure 7.5).

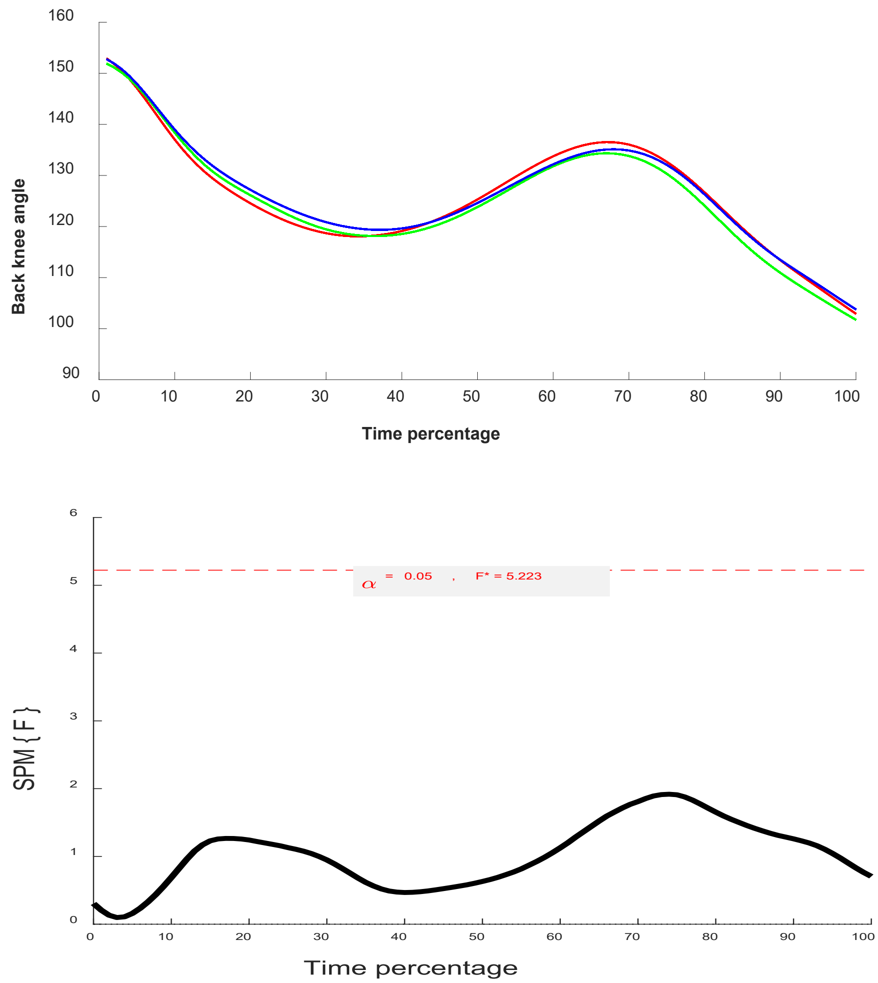


Figure 7.2: Top: Mean time-normalised back knee flexion angle (top) for yorker (red), bouncer (green) and stock (blue) deliveries from back foot contact to ball release. Bottom: Statistical parametric mapping results for the effect of pitch length condition on back knee flexion angle within the one-way repeated measures ANOVA.

3) Front hip flexion angle

The SPM one-way repeated measures ANOVA result didn't reveal any significant differences ($p > 0.05$) in front hip flexion angle from back foot contact to ball release among the three variations (Figure 7.6).

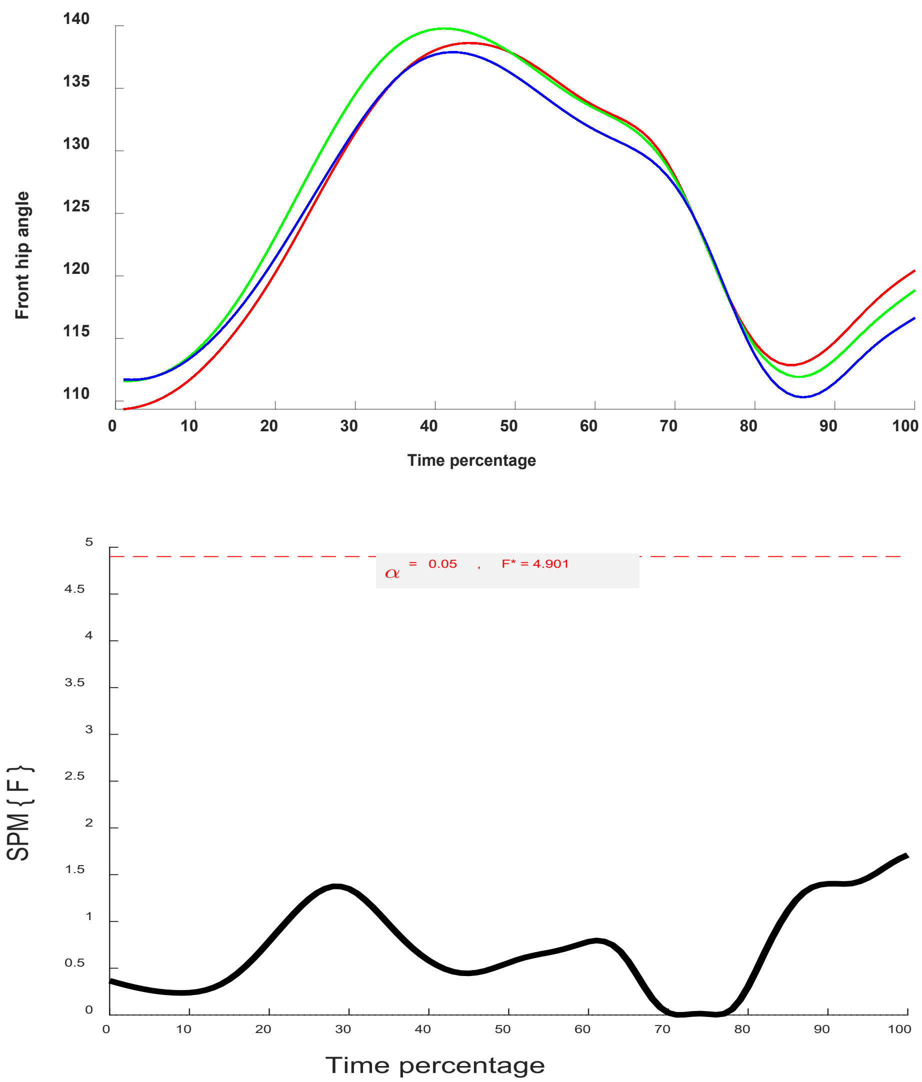


Figure 7.3: Top: Mean time-normalised front hip flexion angle (top) for yorker (red), bouncer (green) and stock (blue) deliveries from back foot contact to ball release. Bottom: Statistical parametric mapping results for the effect of pitch length condition on front hip flexion angle within the one-way repeated measures ANOVA.

4) Front knee flexion angle

The SPM one-way repeated measures ANOVA result didn't reveal any significant differences (p > 0.05) in front knee flexion angle from back foot contact to ball release among the three variations (Figure 7.7).

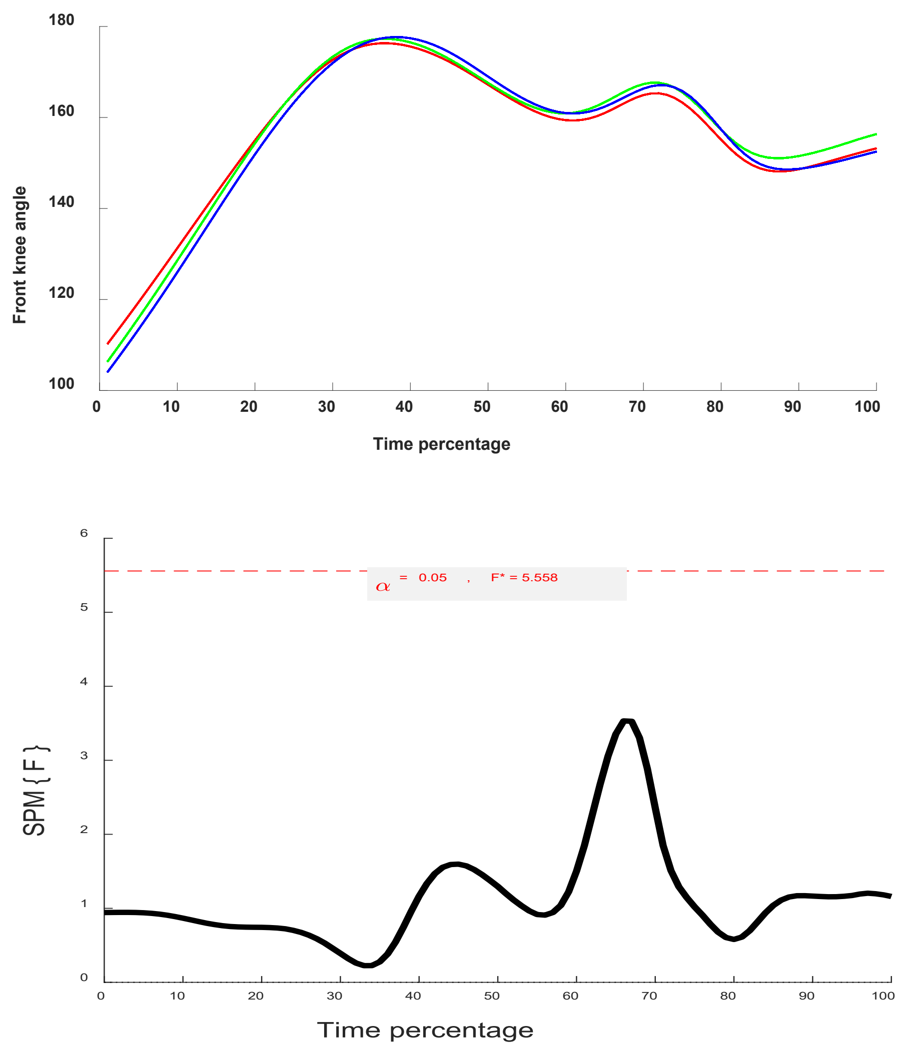


Figure 7.4: Top: Mean time-normalised front knee flexion angle (top) for yorker (red), bouncer (green) and stock (blue) deliveries from back foot contact to ball release. Bottom: Statistical parametric mapping results for the effect of pitch length condition on front knee flexion angle within the one-way repeated measures ANOVA.

5) Lumbar flexion angle

The SPM one-way repeated measures ANOVA result didn't reveal any significant differences ($p > 0.05$) in lumbar flexion angle from back foot contact to ball release among the three variations (Figure 7.8)

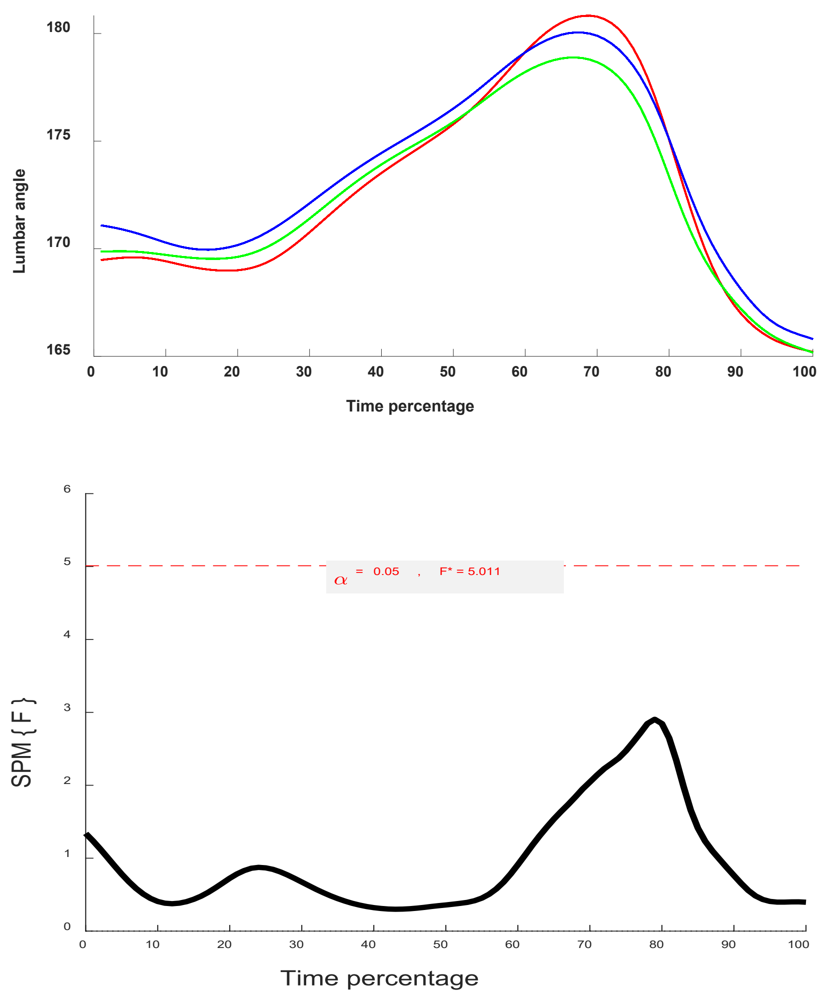


Figure 7.5: Top: Mean time-normalised lumbar flexion angle (top) for yorker (red), bouncer (green) and stock (blue) deliveries from back foot contact to ball release. Bottom: Statistical parametric mapping results for the effect of pitch length condition on lumbar flexion angle within the one-way repeated measures ANOVA.

6) Thoracic flexion angle

The SPM one-way repeated measures ANOVA result revealed significant differences ($p < 0.05$) in thoracic flexion angle from the instance of back foot contact to 30%-time duration from back foot contact to ball release among the three variations. This difference was insignificant ($p > 0.05$) during the mid-part but at last 20% of the time duration before ball release showed significant ($p < 0.05$) differences (Figure 7.9)

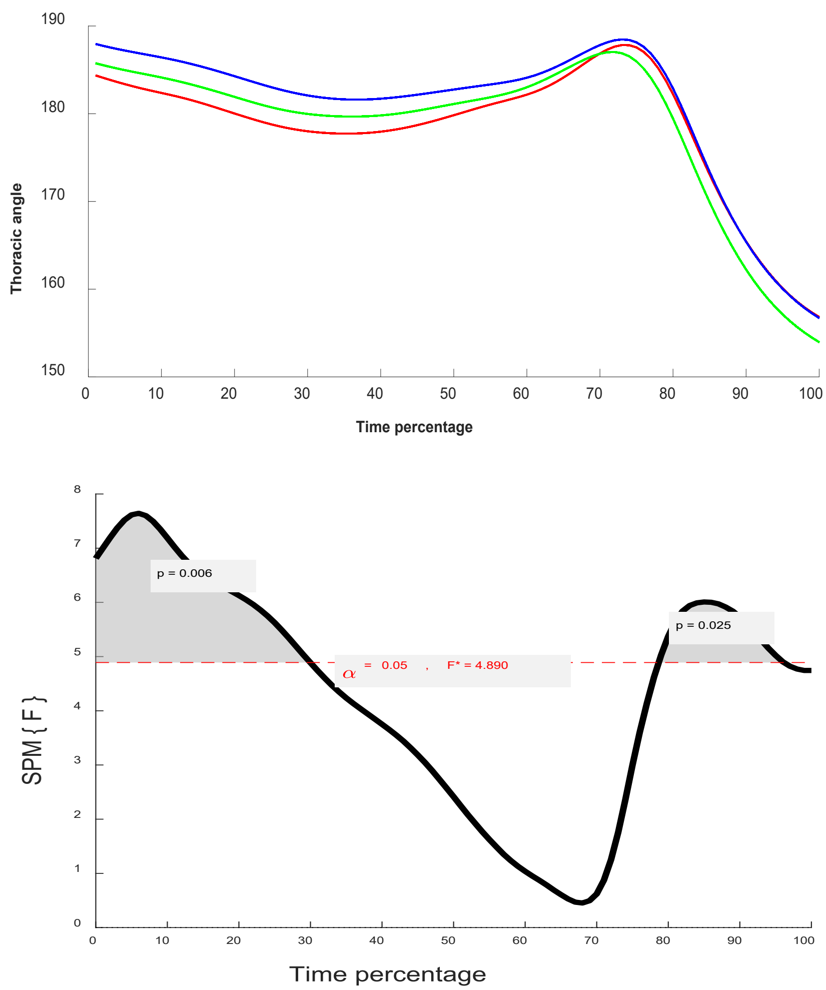


Figure 7.6: Top: Mean time-normalised thoracic flexion angle (top) for yorker (red), bouncer (green) and stock (blue) deliveries from back foot contact to ball release. Bottom: Statistical parametric mapping results for the effect of pitch length condition on thoracic flexion angle within the one-way repeated measures ANOVA.

The post – hoc test revealed that bouncer and stock balls had significant differences similar to the main effect while yorker balls was only significantly different with stock balls up to 40%-time duration from the back foot contact instance (Figure 7.10).

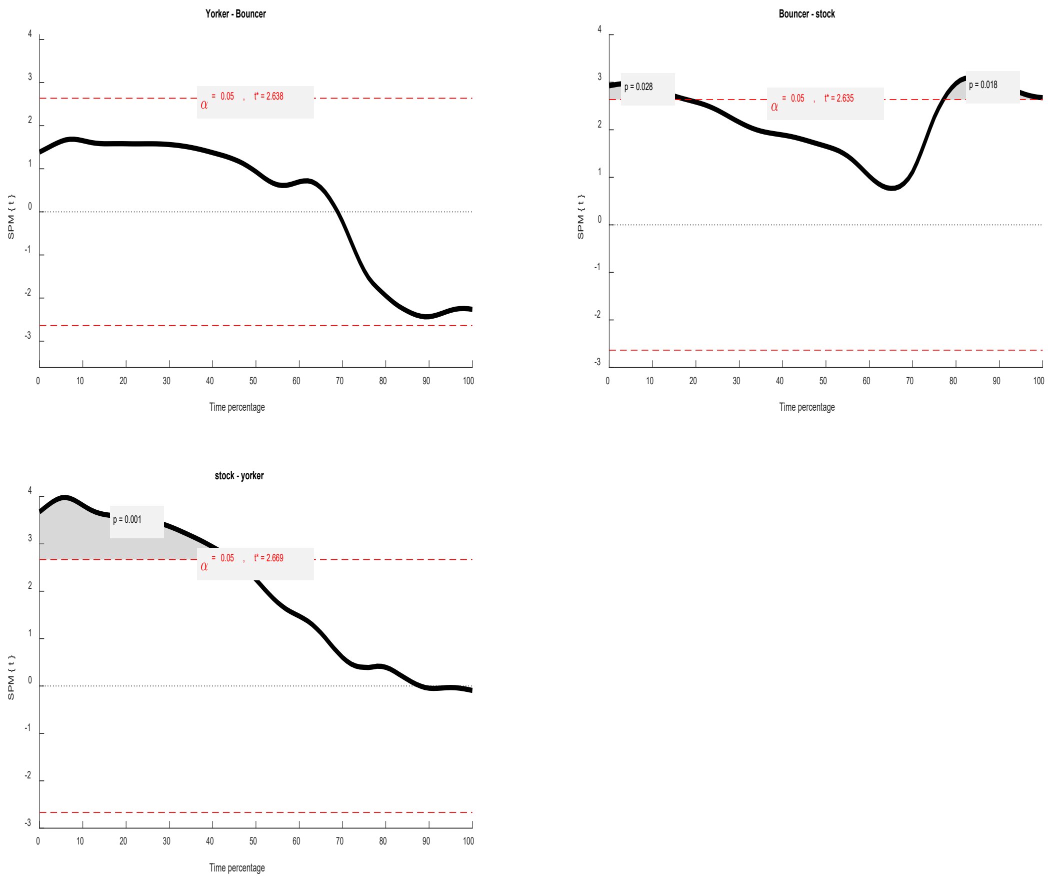


Figure 7.7: Post hoc t tests of yorker – bouncer (left top), bouncer – stock (right top) and stock – yorker (left bottom) variations for thoracic flexion angle.

7) Shoulder flexion angle

The SPM one-way repeated measures ANOVA result didn't reveal any significant differences ($p > 0.05$) in shoulder flexion angle from back foot contact to ball release among the three variations (Figure 7.11).

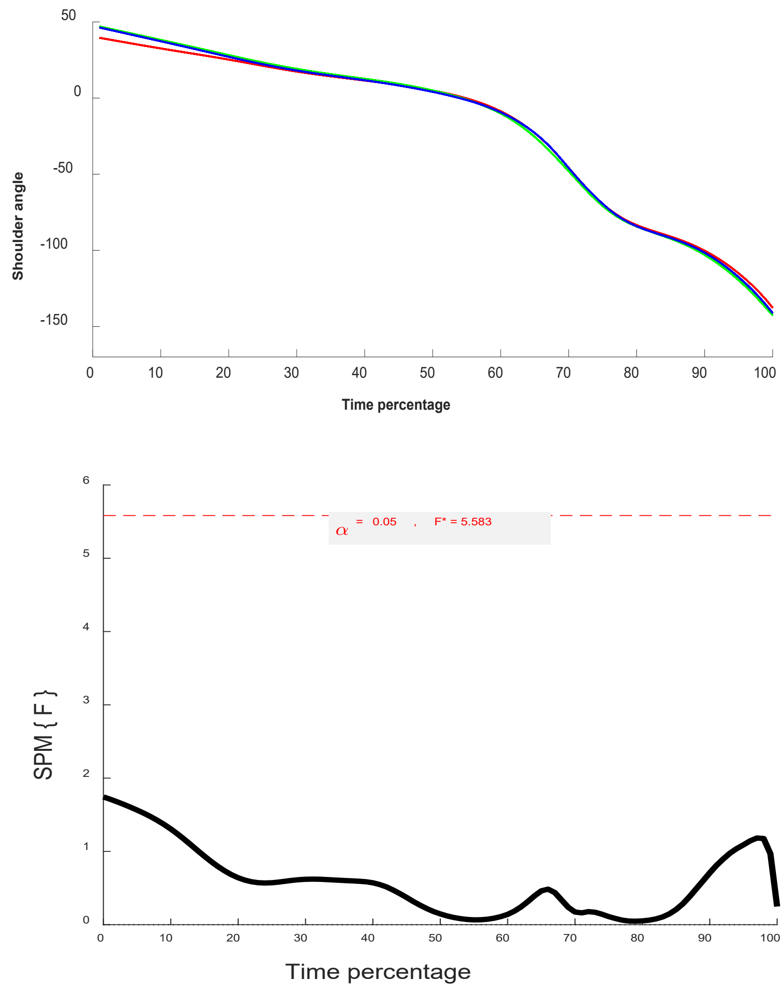


Figure 7.8: Top: Mean time-normalised shoulder flexion angle (top) for yorker (red), bouncer (green) and stock (blue) deliveries from back foot contact to ball release. Bottom: Statistical parametric mapping results for the effect of pitch length condition on shoulder flexion angle within the one-way repeated measures ANOVA.

8) Wrist flexion angle

The SPM one-way repeated measures ANOVA result revealed significant differences ($p < 0.05$) in wrist flexion angle from 40%-time duration from back foot contact to ball release until the ball release instance among the three variations. (Figure 7.12)

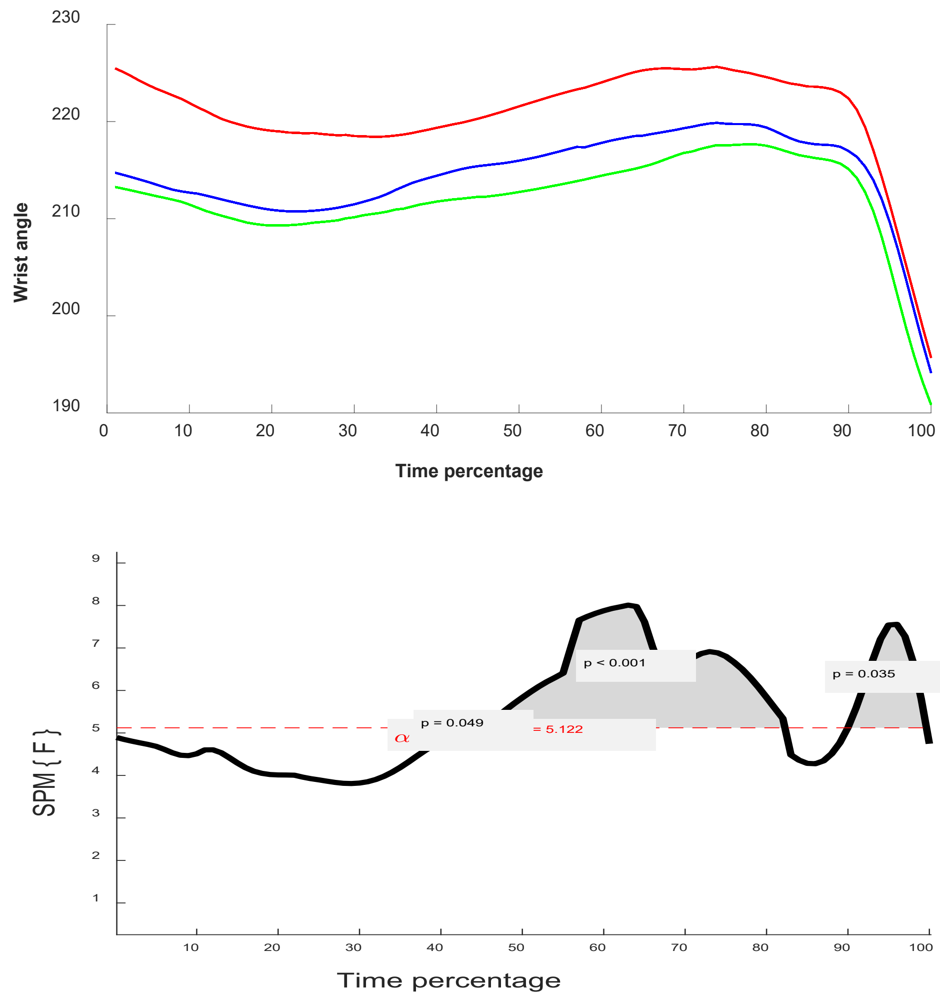


Figure 7.9: Top: Mean time-normalised wrist flexion angle (top) for yorker (red), bouncer (green) and stock (blue) deliveries from back foot contact to ball release. Bottom: Statistical parametric mapping results for the effect of pitch length condition on wrist flexion angle within the one-way repeated measures ANOVA.

The post – hoc test revealed that bouncer and stock balls had no significant difference at the wrist flexion until the very last moment before ball release. Yorkers and bouncers were significantly different ($p < 0.05$) throughout the period while stock and yorkers were significantly different until the ball release but showed no difference at the ball release instance (Figure 7.13).

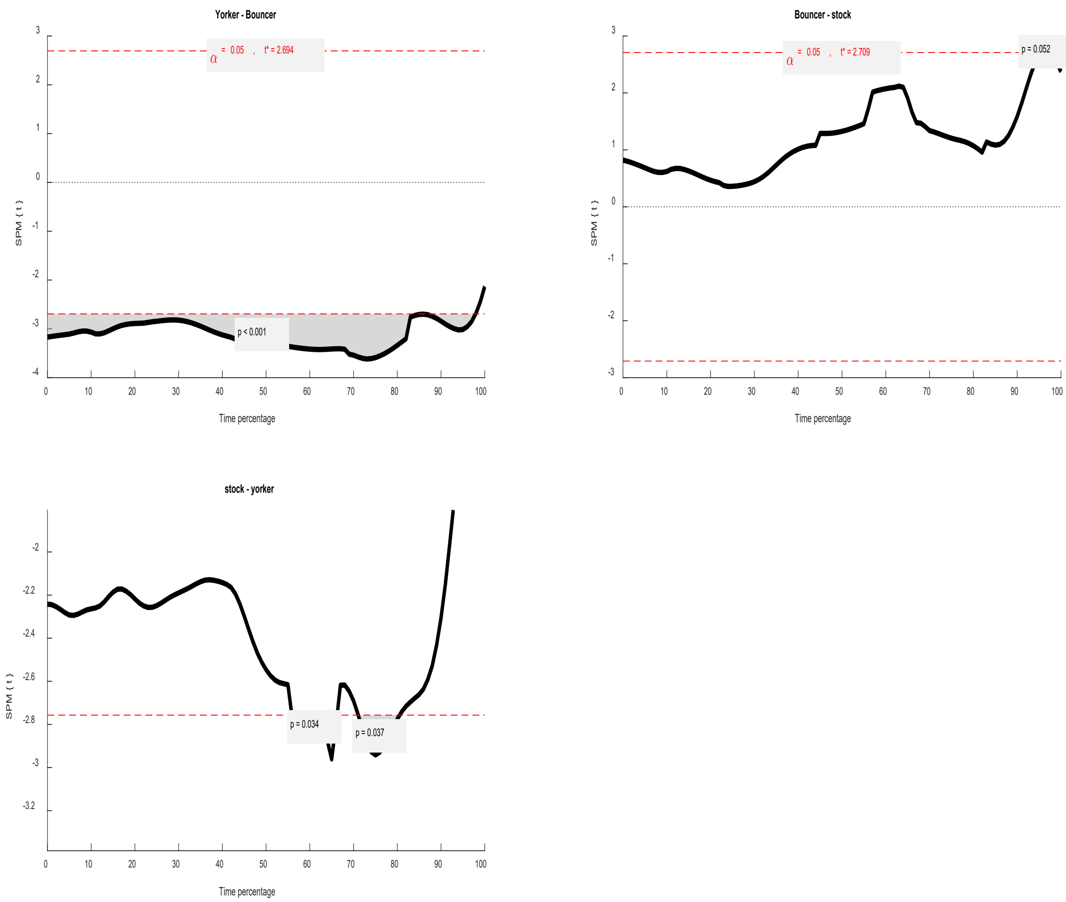


Figure 7.10: Post hoc t tests of yorker – bouncer (left top), bouncer – stock (right top) and stock – yorker (left bottom) variations for wrist flexion angle.

9) 2D thoracic flexion angle

The SPM one-way repeated measures ANOVA result revealed significant differences ($p < 0.05$) in 2D thoracic flexion angle in the last 40%-time duration before ball release instance among the three variations (Figure 7.14).

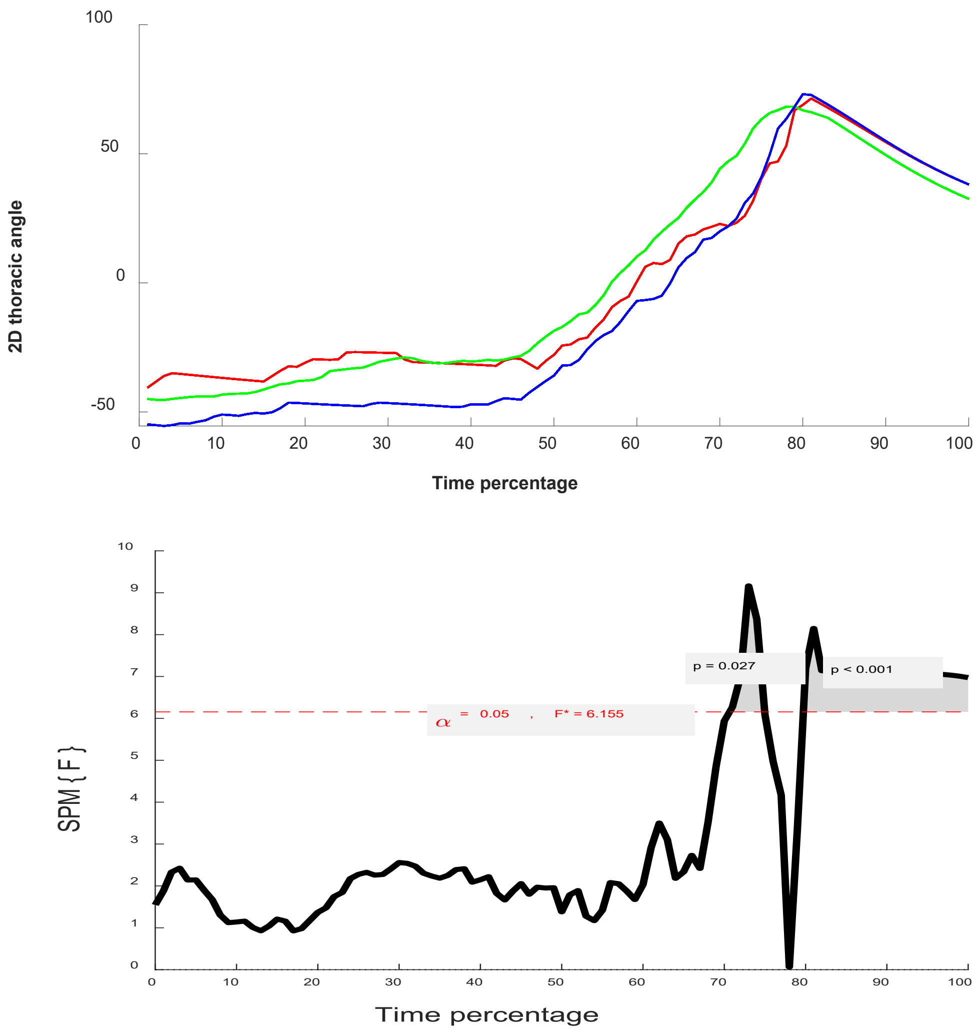


Figure 7.11: Top: Mean time-normalised 2D thoracic flexion angle (top) for yorker (red), bouncer (green) and stock (blue) deliveries from back foot contact to ball release. Bottom: Statistical parametric mapping results for the effect of pitch length condition on 2D thoracic flexion angle within the one-way repeated measures ANOVA.

The post – hoc test revealed that bouncer and stock balls had no significant difference at the 2D thoracic flexion until the very last moment before ball release. Yorkers and bouncers were significantly different ($p < 0.05$) only in the mid part while stock and yorkers had no significant difference throughout the period. (Figure 7.15).

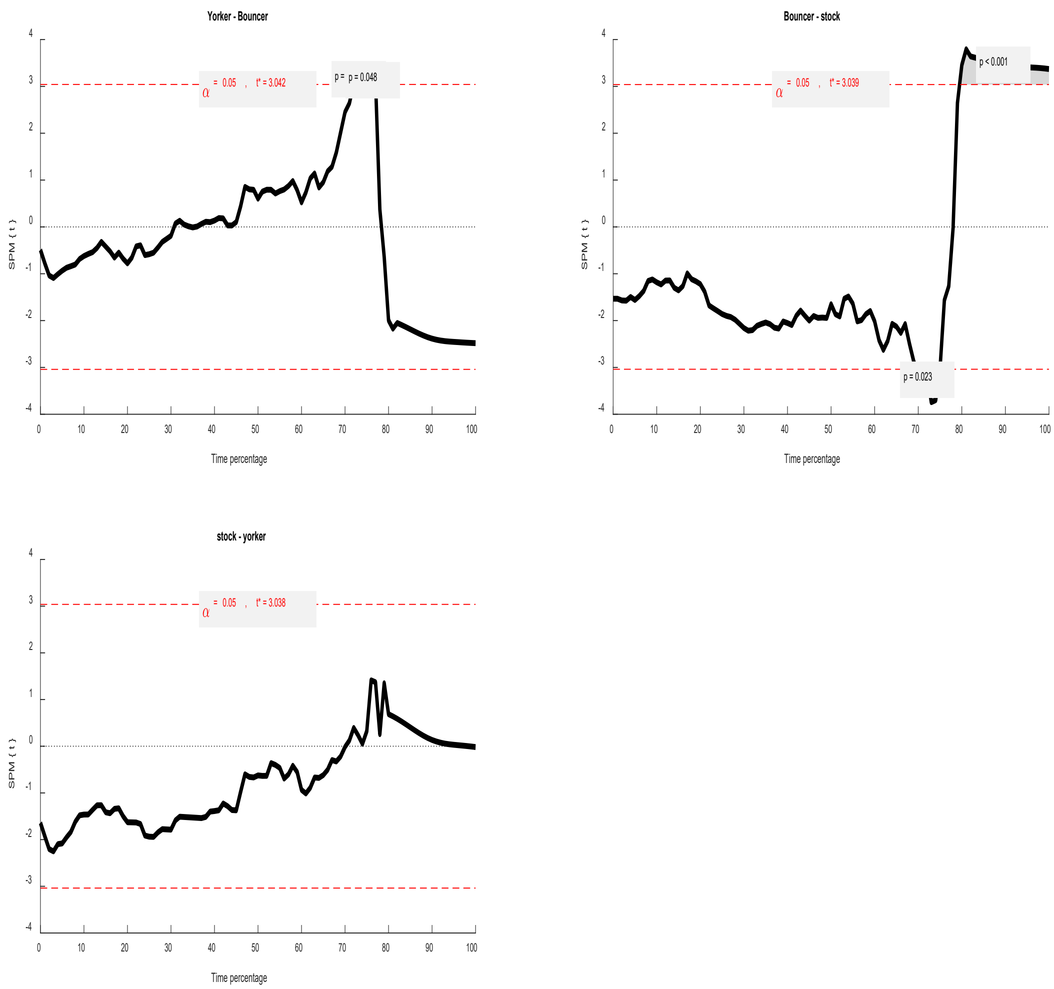


Figure 7.12: Post hoc t tests of yorker - bouncer (left top), bouncer - stock (right top) and stock - yorker (left bottom) variations for 2D thoracic flexion angle.

10) 2D upper arm flexion angle

The SPM one-way repeated measures ANOVA result revealed significant differences ($p < 0.05$) in 2D upper arm flexion angle in the last 20%-time duration before ball release instance among the three variations (Figure 7.16)

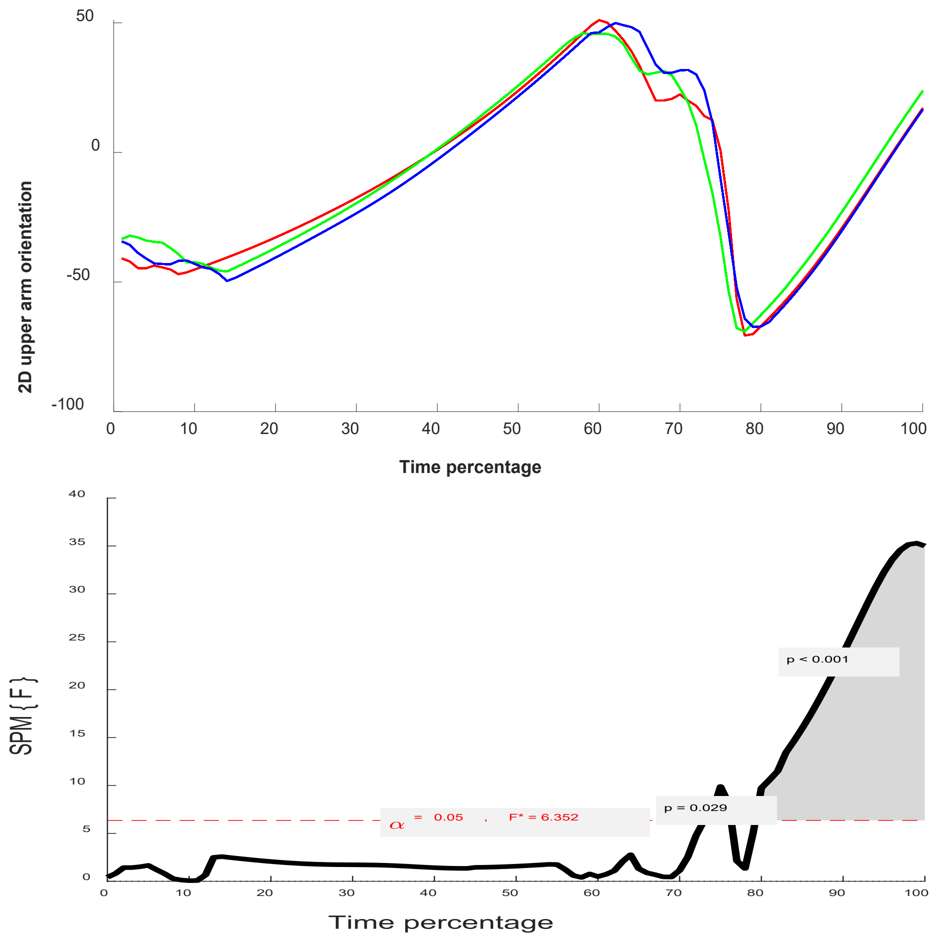


Figure 7.13: Top: Mean time-normalised 2D upper arm flexion angle (top) for yorker (red), bouncer (green) and stock (blue) deliveries from back foot contact to ball release. Bottom: Statistical parametric mapping results for the effect of pitch length condition on 2D upper arm flexion angle within the one-way repeated measures ANOVA.

The post – hoc test revealed that bouncer and stock along with bouncer and yorkers had similar significant changes ($p < 0.05$) at the 2D upper arm angle in the last 20% time duration as the main effect. Stock and yorker balls had no significant difference at the 2D upper arm flexion throughout the period (Figure 7.17).

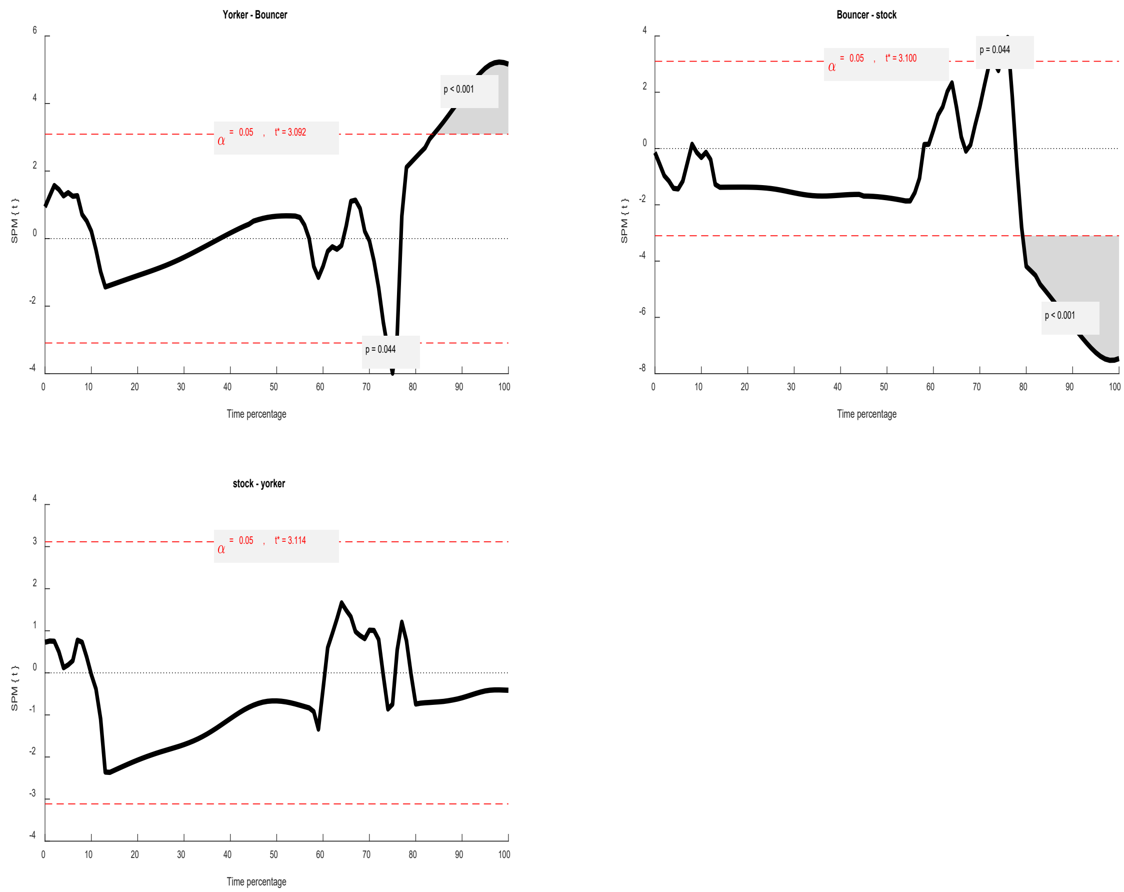


Figure 7.14: Post hoc t tests of yorker – bouncer (left top), bouncer – stock (right top) and stock – yorker (left bottom) variations for 2D upper arm angle.

11) 2D hand flexion angle

The SPM one-way repeated measures ANOVA result revealed significant differences ($p < 0.05$) in 2D hand flexion angle in the last 10%-time duration before ball release instance among the three variations (Figure 7.18)

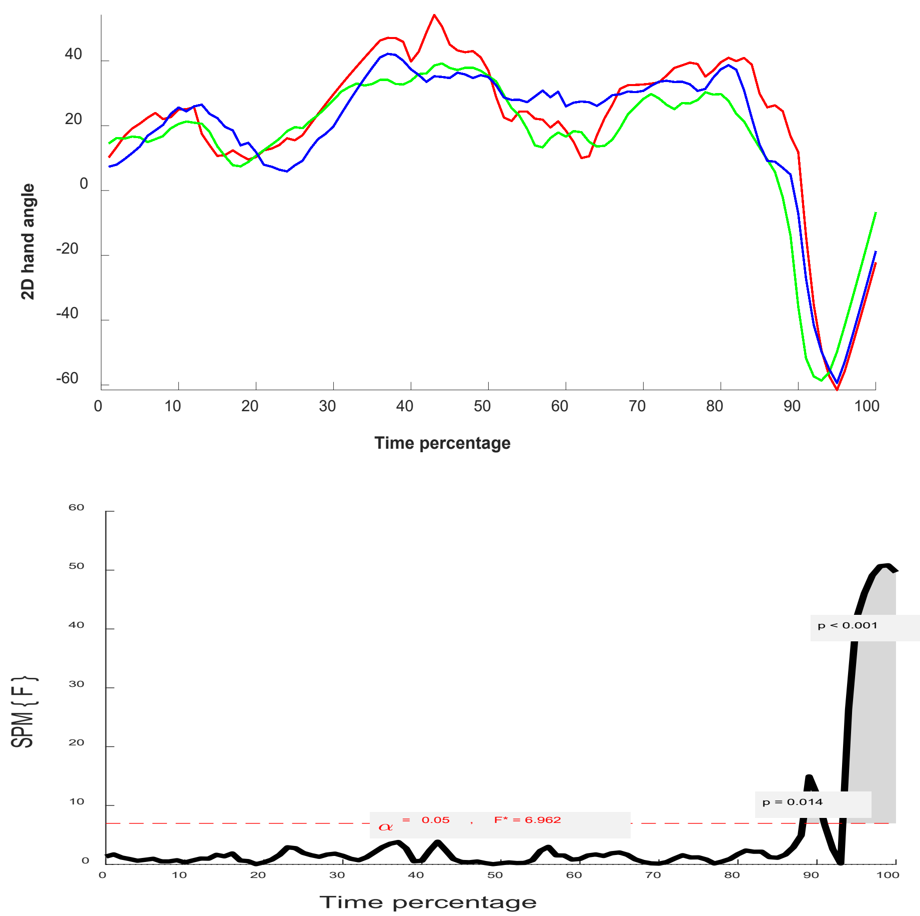


Figure 7.15: Top: Mean time-normalised 2D hand flexion angle (top) for yorker (red), bouncer (green) and stock (blue) deliveries from back foot contact to ball release. Bottom: Statistical parametric mapping results for the effect of pitch length condition on 2D hand flexion angle within the one-way repeated measures ANOVA.

The post – hoc test revealed that bouncer and stock along with bouncer and yorkers had similar significant changes ($p < 0.05$) at the 2D hand flexion angle in the last 10 % time duration as the main effect. Stock and yorker balls had no significant difference at the 2D upper arm flexion throughout the period (Figure 7.19).

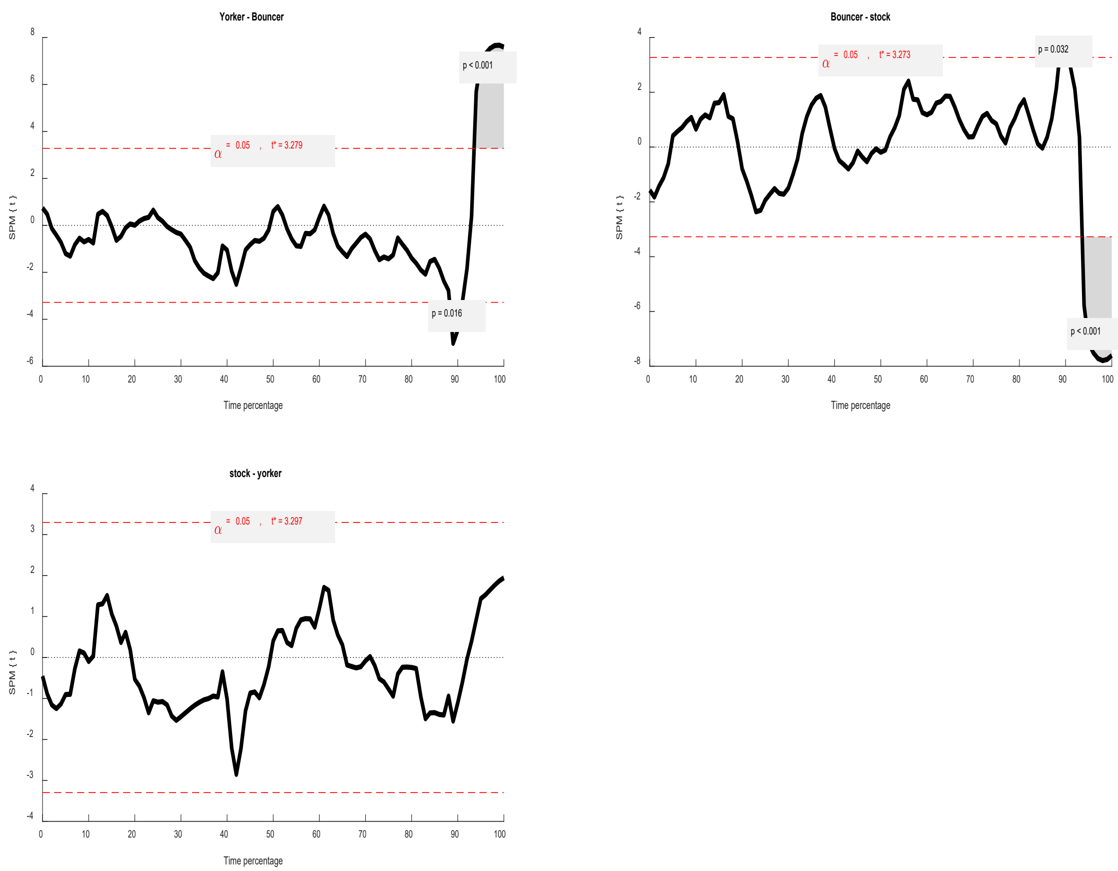


Figure 7.16: Post hoc t tests of yorker – bouncer (left top), bouncer – stock (right top) and stock – yorker (left bottom) variations for 2D hand flexion angle.

12) Vertical velocity of the COM

The SPM one-way repeated measures ANOVA result didn't reveal any significant differences ($p > 0.05$) in vertical velocity of the center of mass from back foot contact to ball release among the three variations (Figure 7.20)

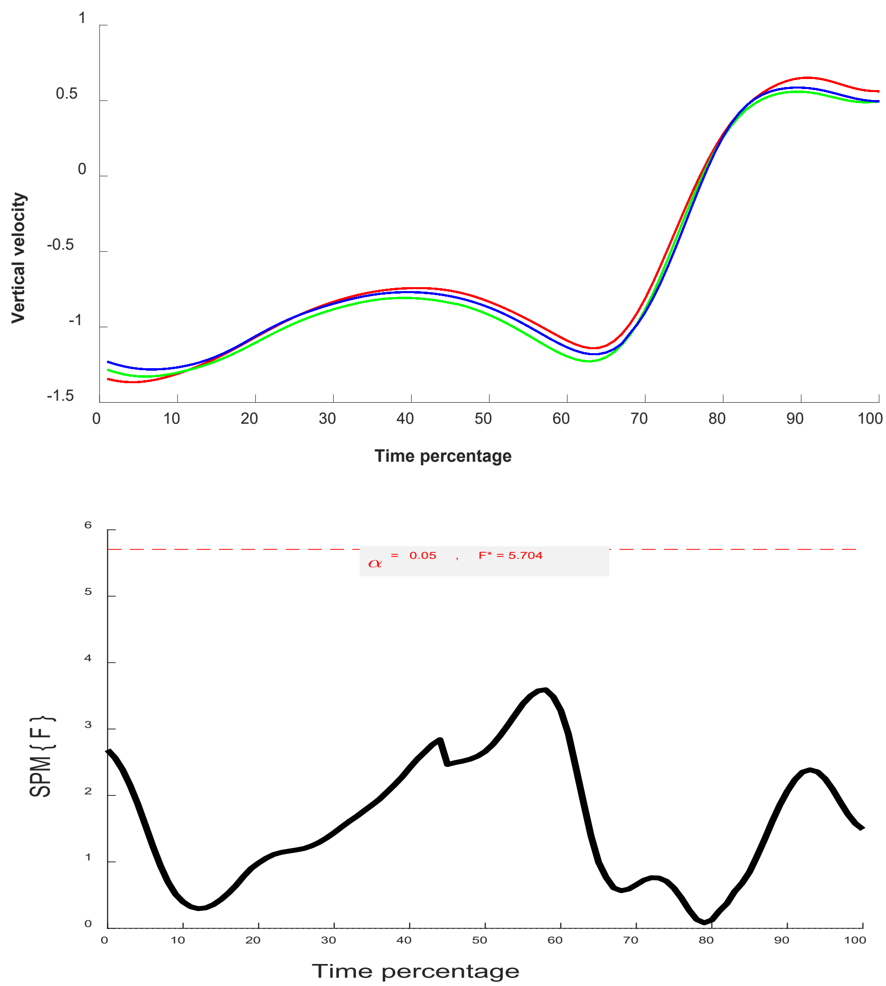


Figure 7.17: Top: Mean time-normalised vertical velocity of COM (top) for yorker (red), bouncer (green) and stock (blue) deliveries from back foot contact to ball release. Bottom: Statistical parametric mapping results for the effect of pitch length condition on vertical velocity of COM within the one-way repeated measures ANOVA

13) Horizontal velocity of the COM

The SPM one-way repeated measures ANOVA result didn't reveal any significant differences ($p > 0.05$) in horizontal velocity of the center of mass from back foot contact to ball release among the three variations (Figure 7.21)

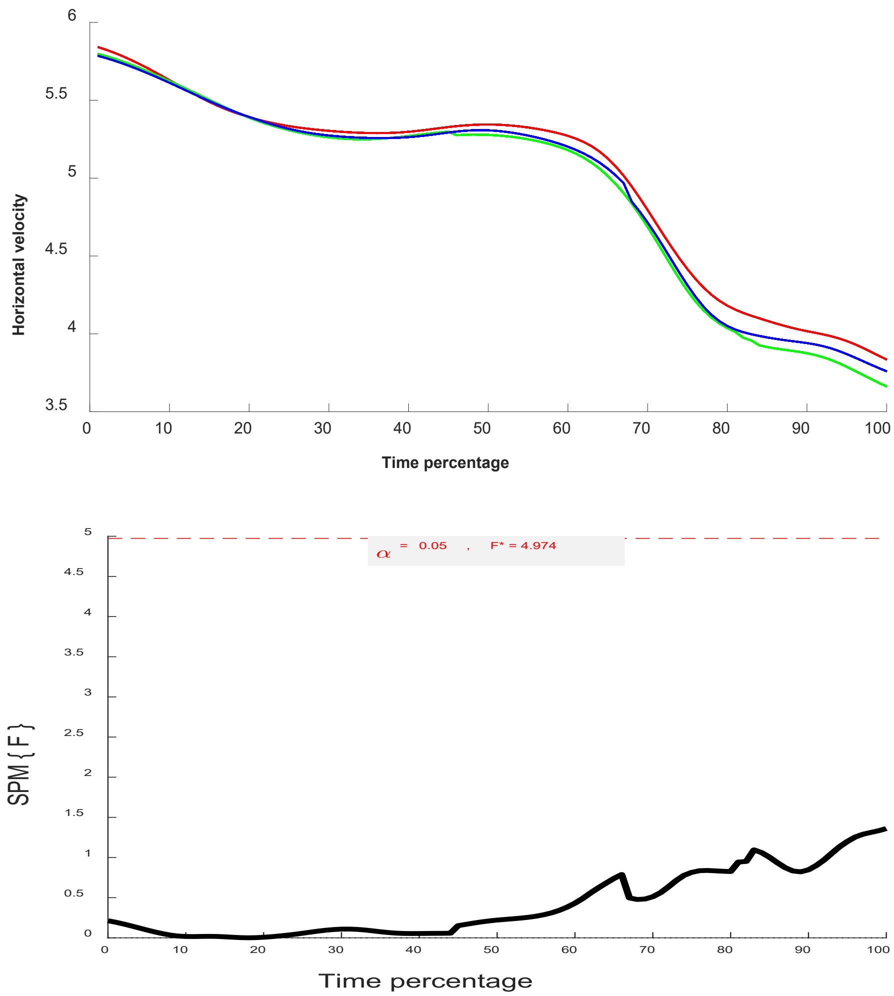


Figure 7.18: Top: Mean time-normalised horizontal velocity of COM (top) for yorker (red), bouncer (green) and stock (blue) deliveries from back foot contact to ball release. Bottom: Statistical parametric mapping results for the effect of pitch length condition on horizontal velocity of COM within the one-way repeated measures ANOVA.

Table 7.2: Summary of statistical parametric mapping results with F statistic value in the continuous analysis

kinematic variable	SPM F value	P value and time range	between groups
Back hip angle	5.2	P > 0.05	-
Back knee angle	5.2	P > 0.05	-
Front hip angle	4.9	P > 0.05	-
Front knee angle	5.6	P > 0.05	-
Lumbar angle	5.0	P > 0.05	-
Thoracic angle	4.9	P = 0.006 (0-30%) P = 0.025 (80% - 100%)	S -B Y – B (almost)
Shoulder angle	5.6	P > 0.05	-
Wrist angle	5.1	P < 0.001 (40%-80%) P = 0.035 (90% - 100%)	Y – B Y -S (final part)
2D thoracic angle	6.1	P < 0.001 (70% - 100%)	S -B Y – B (almost)
2D upper arm angle	6.3	P < 0.001 (80% - 100%)	S -B Y – B
2D wrist angle	7.0	P < 0.001 (90% - 100%)	S -B Y – B
Vertical velocity of the COM	5.7	P > 0.05	-
Horizontal velocity of the COM	5.0	P > 0.05	-

- Y- B denotes significant difference between yorker and bouncer
- Y -S denotes significant difference between yorker and stock
- S – B denotes significant difference between stock and bouncer

Lower body joint angles (back knee, back hip, front knee, and front hip) and lumbar-pelvic angles didn't reveal any significant effect of the pitch length condition at any time in the movement. The thoracic angle differed significantly between bouncer and other conditions. Bouncers had a more flexed thoracic angle than others in the final part before the ball release instance. Interestingly, wrist angle revealed a more extended angle for yorker condition from the start of the back foot contact phase until the ball release. While yorkers were significantly different from bouncers in mid part of the back foot to front foot stride, showed significant change from stock balls in the final 10% duration just before the ball release. The 2D orientation of thoracic and hand segments revealed significant differences in the last 10% - 20% time which were already identified as predictive parameters for ball release height and the ball release angle in the previous chapter discrete analysis. The vertical velocity or the horizontal velocity of the center of mass didn't show any difference which reveals that the bowlers run up haven't change much among the variations.

7.7 Discussion

Previous chapters revealed parameters at ball release that were associated with those ball release parameters ultimately affecting pitch length. In this study, fast bowling pitch length variations were compared to identify differences in continuous joint angles from back foot contact to ball release. The previous chapter focused on a discrete data analysis at the ball release instance to find out the best technique parameters associated with pitch length variations. Similar analysis was done in this study to initiate the analysis.

The discrete ANOVA revealed significance differences between the three pitch length variations for all ball-specific parameters at ball release (release speed, release angle, relative release height). Ball release angle (η^2= 0.78) and release height (η^2= 0.22) showed high and moderate effect sizes, respectively. The main technique factors associated with changes in these ball-specific parameters were investigated. Although front knee flexion was described as mainly correlated with ball release speed in a previous study (Worthington et al., 2013), it was not a differing factor between pitch length variations.

Thoracic angle had clear differences from the beginning of back foot contact where stock balls had a greater extension than bouncers and yorkers. This difference became minimal at the point of front foot contact which suggests bouncers and yorkers having a gradual increase of thoracic extension compared to the stock balls. Again, after the front foot contact bouncer balls had the same amount of increased thoracic flexion where stock and yorker balls had a similar kind of a reduced flexion compared to bouncers. This indicates the higher thoracic movement and involvement in bouncer balls than other variations. This supports the findings of Worthington (2013) where higher thoracic flexion positively corelated with higher ball release speeds. Although the resultant ball release speeds have no significant difference among the pitch length conditions, the vertical vector of release speed is highly influenced in bouncer balls due to this higher amount of flexion. As the thoracic flexion was found out to be significantly different in bouncers than other conditions in the previous chapter in discrete analysis at the point of ball release this study confirms that the movement or the change among the conditions have started since the front foot contact instance.

Moreover, thoracic flexion at ball release was found to be significantly contributing to the ball speed in previous studies (Davis and Blanksby, 1976b; Elliot et al., 1986). This study revealed that the highest thoracic flexion is occurred when bowling a bouncer and the flexion becomes significantly different from other variations in the last 20% of time duration during the delivery stride. In the previous chapter it was found that average release speeds of bouncers were slightly faster than other variations even it was concluded as not significant. This is a good starting point for further studies to find out any inter connection among ball speed and ball pitch length even though this study has less evidence for a statement.

Wrist flexion at ball release and 2D orientation of hand segments revealed significant differences between pitch length conditions. Wrist angle had a similar type of a flexion movement at the same time in all the variations but the yorkers maintained a more extended angle than the other two group types since the start of the back foot contact phase. This difference became minimal at the point of ball release which indicates more wrist flexion and wrist involvement in yorker balls in the last phase of the fast-bowling technique. Although the motion of the wrist again supports the findings in the previous chapter which revealed significant flexion of the wrist at the point of ball release for bouncers, this study revealed higher flexion of the wrist in yorkers than other two variations in the continuous analysis starting from the back foot contact instance. The findings explains that although a higher flexed wrist supports the path of the bouncer ball at the ball release instance, higher wrist movement is needed for yorker balls than other variations between back foot contact to ball release. The previously mentioned extended wrist angle at back foot contact instance indicates the players trying to acquire a more cocked or an extended position while gripping the ball when intending to ball a yorker. Furthermore, this study provides evidence that this change has been a continuous development since the front foot contact phase. Although wrist flexion was found to be contributing 5% - 22% in increasing ball release speed previously (Davis and Blanksby, 1976a, Elliott et al., 1986), this couldn't be linked to this study where there was no significant difference ball release speed among the variations.

Shoulder angle differences were insignificant although the 2D upper arm angle revealed significant differences among the variations. This is a result of thoracic flexion as the whole upper body 2D orientation changes without any shoulder joint angle change. Previous studies have targeted on investigating the shoulder and arm positions at ball release and its relationship with ball release speed (Elliot et al., 1986; Burden and Bartlett, 1989, Foster et al., 1989, Burden, 1990) which revealed the upper arm to be further behind the trunk line at release for a faster delivery. Although this study was investigating for possible changes among the variations in a continuous analysis, any significant change was not found from the back foot contact to ball release.

7.8 Conclusion

This study reported a comparison of joint angles during the key phases of fast bowling action between different pitch length conditions. The previous chapters suggest significant differences in thoracic angle and wrist angle at ball release between different pitch length conditions, while shoulder angle at ball release was correlated with the pitch length. This chapter revealed that these changes are occurring from the start of the back foot contact position where players tend to have a more extended or cocked wrist position for a higher wrist flexion when they are intending to bowl a yorker. Higher thoracic flexion was also found to be a decisive factor when intending for bouncers which was a continuous flexion from the backfoot contact until the ball release which made a significant difference. The overall objectives in terms of kinematic parameters of the thesis were investigated in Chapter 6 and 7.

CHAPTER 8

THE EFFECTS OF JOINT MOMENTS ACTING ON THE UPPER BODY ON DIFFERENT LENGTH DELIVERIES IN CRICKET FAST BOWLING

8.1 Abstract

Cricket fast bowling biomechanics have mostly identified different key kinematic technique parameters and joint loading mechanics for higher ball release speeds and injury concerns in discrete analyses. Although ball release speed is still a major factor, different fast bowling variations can also reduce batting performance. In this study joint moments in the upper body were investigated from back foot contact to ball release in a continuous and a discrete analysis as a continuation to the kinematic findings revealed in previous chapter among the three common pitch length deliveries; stock (4 - 7 m), yorker (0 - 2 m), and bouncer (> 7 m). Data were collected from twenty-one county level fast bowlers who each performed forty-eight deliveries (twenty-four stock, twelve bouncers and twelve yorkers). An eighteen camera (MX13) Vicon motion analysis system (250 Hz) and a Kistler force plate (1000 Hz) was used to capture the actions, with a fifty-three-marker model specifically developed for fast bowling analysis plus two (tape) ball markers used. Two dimensional direct linear transformation was used to calculate the pitch length of each trial from rear camera view video recordings. A top-down inverse dynamics method was used to calculate the joint moments in the upper body joints (wrist, shoulder and thoracic). Initial repeated measures ANOVA didn't reveal ($p > 0.05$) any significant difference among the pitch length conditions for the vertical force, braking force and loading rates. The continuous analyses also didn't show any significant differences, but yorker balls revealed reduced vertical and braking forces from front foot contact to ball release than bouncers and stock. Although, one-dimensional statistical parametric mapping analysis reported significant changes ($p = 0.03$) in wrist moment for bouncers between front foot contact to ball release for a brief period (40% - 60% duration) it was not significant at the ball release instance. A lower angular velocity of the wrist was revealed in bouncers at the start of front foot contact to ball release, but it could not explain

the small wrist moment change among the conditions as the angular velocity differences was not significant in the one-dimensional statistical parametric mapping analysis. Although shoulder moment and shoulder angular velocity explained up to 45.3% of the shoulder angle change at the ball release instance, the regression models couldn't explain the changes of wrist angle and thoracic angle change which were significant at the ball release instance in the previous kinematic analysis.

8.2 Introduction

Cricket fast bowlers uses the run-up momentum and other kinematic and kinetic variables to deliver the ball faster and accurately. The kinematic variables are investigated up to the ball release instance in most of the previous studies (Tyson, 1976; Bartlett et al., 1996; Ranson, 2008) and different technique parameters were found to be important in important for a higher release speed. However, the latest additions of the game and reduction of overs in cricket matches, have favored the batters to score highly. Recent studies on fast bowling performance biomechanics have shifted to finding out the importance and technique variables associated with fast bowling variations.

Most of the studies which has targeted fast bowling variations has reported only the kinematic technique parameter changes among the different variations (Sarpeshkar et al., 2017; Woolmer et al., 2008). Callaghan et al. (2021), reported no significant difference in whole body biomechanical loading among different pitch length variations in a discreet and a continuous analysis. Furthermore, few studies investigated the variations in non - bowling arm torques to find out the differences in different speed grouped players. And highest peak shoulder flexion/ extension torques were present at the ball release instance of the bowling arm. Thoracic flexion had a peak value in the early stages of the front foot to ball release phase which was significantly different from the shoulder torques (Ferdinands, 2015).

In the previous study, it was revealed that upper body joint kinematics explains the variance of ball pitch length into a higher percentage while the lower body remains the same among the pitch length groups.

This study aims, to investigate any difference in joint torques and segmental angular velocity variations among the pitch length groups.

8.3 Methodology

Twenty-one elite fast bowlers (mean ± standard deviation: height 1.87 ± 0.05 m, body mass 81.40 ± 9.74 kg) participated in this investigation. All the bowlers were identified as 'fast bowlers' by MCCU and county academy fast bowling coaches and were cleared fit to bowl. Testing procedures were explained to each participant individually in accordance with the Loughborough university ethical guidelines and player consents were signed by each player prior to data collection.

Each bowler was asked to bowl forty-eight (48) deliveries from full length run up. this consisted of twelve (12) bouncer balls, twelve (12) yorker balls, twelve (12) stock balls for right-handed batsmen and twelve (12) stock balls for left-handed batsmen. Only one of either set of twelve stock balls was selected. Some bowlers found it difficult to pitch the ball in the expected 4-7 m margin when they were bowling to one of the left- or right-handed imaginary batters. Considering this, the set of stock balls which was the closest to the expected margin was selected for further analysis. These deliveries were bowled in a randomized order.

The following distances from the batting end stumps were considered for the classification of delivery type (i.e., pitch length) as in a previous study (Hazari, 2016):

0 - 2 m: yorker
4 - 7 m: stock ball
> 7 m: bouncer

For the used equipment and the data collection methods see Chapter 3.

Additionally, two permanently installed Kistler force platforms (type 9287CA – 900 x 600 mm) were located at the bowling crease to record front foot contact which operated at 1000 Hz.

8.4 Data processing

For the key instances identification, marker model labelling process, calculation of COM and joint angles see Chapter 4.

Furthermore, the forces acted on the back foot during the back foot contact to ball release instance was not collected as the force plate was placed for the readings in the front foot during the fast-bowling action. Therefore, to calculate the joint torques acting on the upper body during the cricket fast bowling action a kinetic chain was explained starting from the top. The top-down method had less errors when calculating joint torques for the upper body as the calculation is started from the distal end of the hand (Figure 8.4).

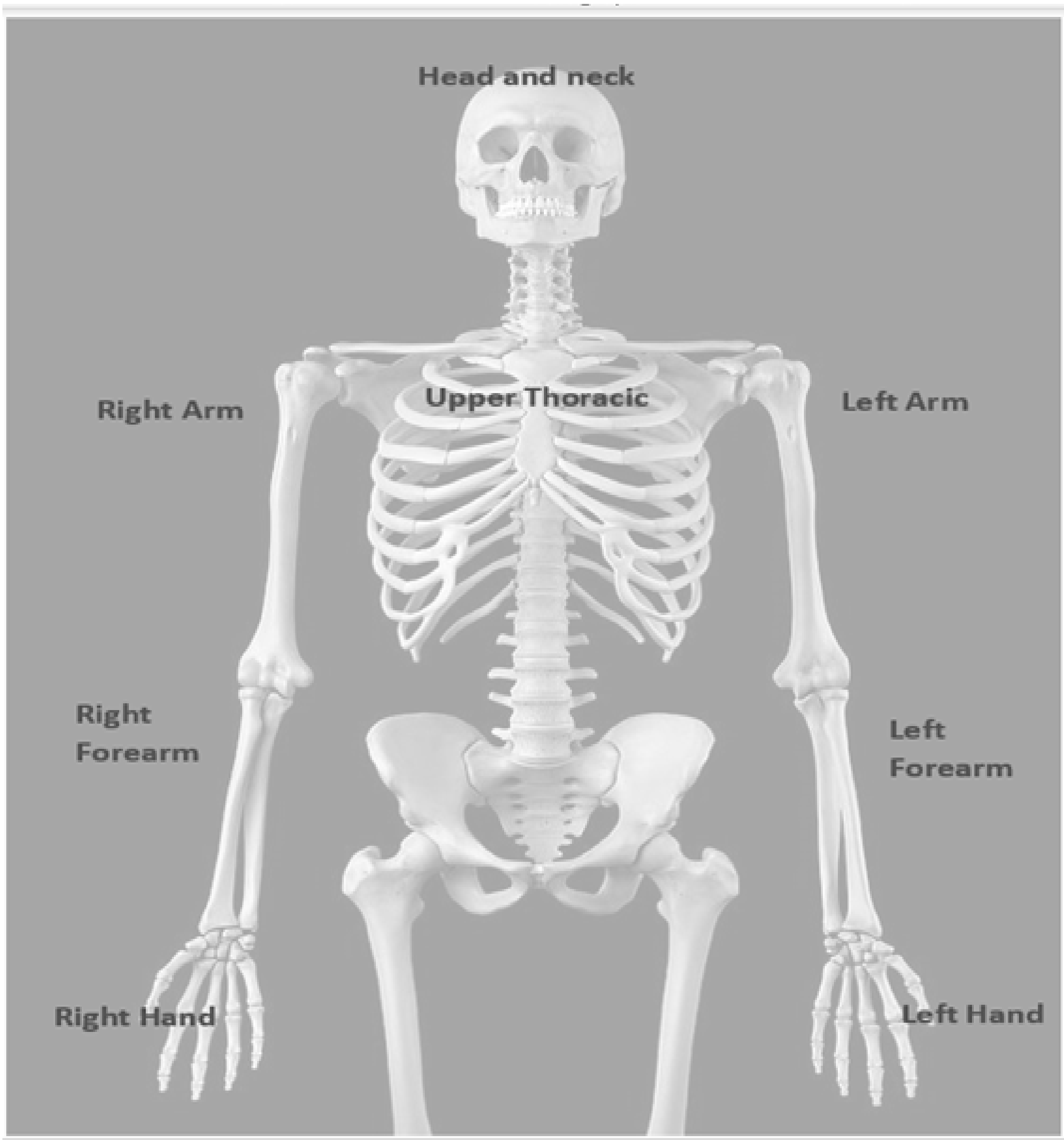


Figure 8.1: upper body segments (in a skeleton) used for calculations of joint moments in "top - down" method.

8.5 Statistical analysis

Discrete point analyses were performed within the Statistical Package for the Social Sciences (SPSS v 25.0). A one-way repeated measures analysis of variance (ANOVA) compared key kinetic parameters at key instances between the three pitch length conditions. Where significant ($p < 0.05$) main effects were reported, post hoc tukey test statistics compared individual conditions. Three trials from each player were included in the analysis including one from each variation as they were separate data points unrelated to each other.

Continuous analyses of the time normalized kinetic parameters were performed through statistical parametric mapping (SPM1D.org) one-way repeated measures ANOVAs in MATLAB to investigate the differences between the deliveries. Similar to the discrete analysis, where significant ($p < 0.05$) main effects were reported, post hoc tukey test was used to compare individual conditions.

8.6 Results

Table 8.1: Descriptive, significance and effect sizes of the interested kinetic parameters at lower extremity in fast bowling action among different pitch length groups

parameter	yorker (mean ± std) (range)	bouncer (mean ± std) (range)	stock (mean ± std) (range)	ANOVA p-value (multiple comparisons)	effect size η2
Ball speed (R) (ms^{-1})	31.5 ± 2.3 (24.7 - 37.7)	33.1 ± 2.2 (25.2 - 40.0)	32.1 ± 1.9 (28.5 - 37.2)	< 0.001 (A, C)	0.08
Brake force at FFC (BW)	-0.07 ± 0.22 (-0.66 -0.12)	-0.11 ± 0.27 (-0.89 – 0.31)	-0.09 ± 0.21 (-0.58 – 0.21)	0.880	0.001
Vertical force at FFC (BW)	1.01 ± 1.02 (0.1 – 4.4)	1.28 ± 1.17 (0.14 – 4.9)	1.18 ± 1.01 (0.17 – 4.18)	0.717	0.006
Braking force at BR (BW)	-0.03 ± 0.31 (-0.92 – 0.49)	0.004 ± 0.24 (-0.70 – 0.50)	0.02 ± 0.23 (-0.43 – 0.52)	0.800	0.004
Vertical force at BR (BW)	1.14 ± 0.68 (0.00 – 2.69)	1.22 ± 0.41 (0.71 – 2.38)	1.20 ± 0.42 (0.37 – 1.97)	0.877	0.012
Peak brake force (BW)	2.61 ± 0.98 (0.47 – 4.0)	3.02 ± 0.86 (1.67 – 4.2)	3.00 ± 0.91 (1.24 – 4.77)	0.305	0.014
Peak vertical force (BW)	5.06 ± 1.52 (1.78 – 8.16)	5.80 ± 1.44 (3.13 – 7.92)	5.75 ± 1.56 (2.61 – 8.36)	0.238	0.008
Time to peak brake force	25.2 ± 8.5 (8.6 – 39.1)	23.0 ± 7.9 (5.6 – 33.0)	22.9 ± 8.7 (2.5 – 35.7)	0.632	0001
Time to peak vertical force	20.3 ± 13.5 (8.5 – 40.0)	17.6 ± 9.6 (5.7 – 32.1)	19.4 ± 10.1 (2.2 – 36.3)	0.733	0.007
Horizontal impulse (BW)	-0.09 ±0.03 (-0.15 – (-0.01)	-0.10 ± 0.02 (-0.13 – (-0.06)	-0.09 ± 0.02 (-0.14 -(-0.04)	0.49	0.021
Vertical impulse (BW)	0.22 ± 0.07 (0.02 – 0.30)	0.26 ± 0.04 (0.17 – 0.32)	0.25 ± 0.04 (0.13 – 0.33)	0.12	0.028
Horizontal loading rate (BWS^{-1})	86.6 ± 49.8 (30.8 – 225.4)	104.2 ± 56.4 (33.2 – 285.5)	101.6 ± 56.3 (32.0 – 273.6)	0.554	0.003
Vertical loading rate (BWS^{-1})	224.6 ±154.7 (72.0 – 667.2)	273.8 ± 157.5 (69.0 – 642.0)	247.7 ± 134.6 (86.8 – 605.5)	0.583	0.011

*A denotes significant difference between yorker and bouncer groups
* B denotes significant difference between yorker and stock groups
* C denotes significant difference between stock and bouncer groups

The kinetic parameters at the front foot contact and ball release instance didn't reveal any significant differences among the pitch length variations ($p > 0.05$). The repeated measures ANOVA showed that braking force, vertical force at front foot contact and ball release instances, peak braking and vertical forces, vertical and horizontal impulses and loading rates had no significant differences among the pitch length conditions ($p > 0.05$).

<u>**Continuous analysis of Brake force from FFC to BR**</u>

The SPM one-way repeated measures ANOVA result didn't reveal any significant differences ($p > 0.05$) in braking force from back foot contact to ball release among the three variations (Figure 8.5).

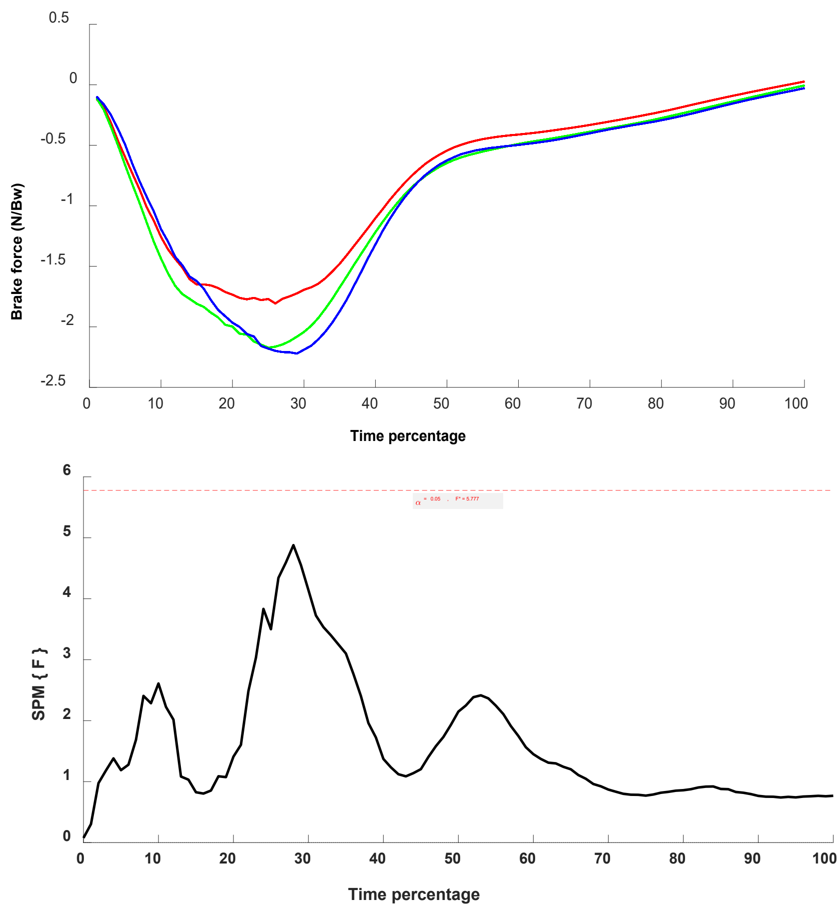


Figure 8.2: Top: Mean time normalised braking force (N.BW-1) for yorker (red), bouncer (green) and stock (blue) deliveries from front foot contact to ball release. Bottom: Statistical parametric mapping results for the effect of pitch length condition on braking force within the one-way repeated measures ANOVA. (dashed line shows the α = 0.05 threshold level for significance).

Continuous analysis of vertical ground reaction force from FFC to BR

The SPM one-way repeated measures ANOVA result didn't reveal any significant differences ($p > 0.05$) in vertical ground reaction force from back foot contact to ball release among the three variations (Figure 8.6).

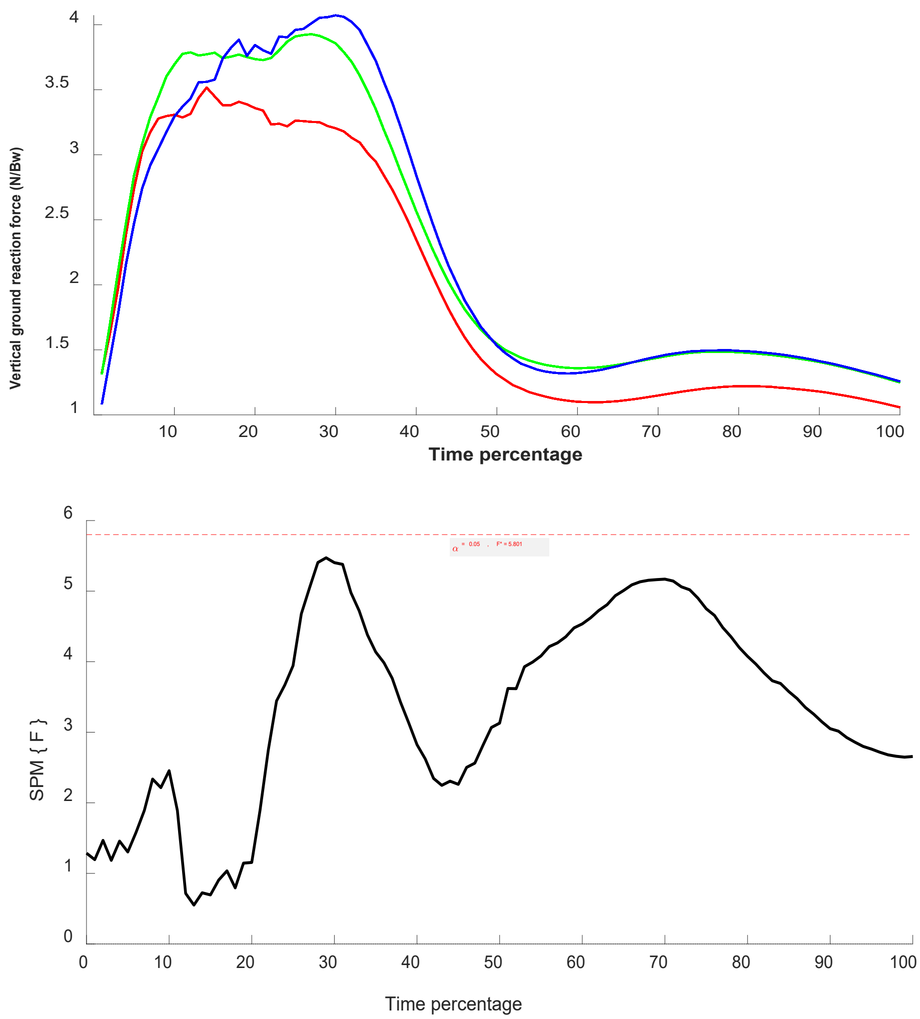


Figure 8.3: Top: Mean time normalised vertical ground reaction force (N.BW-1) for yorker (red), bouncer (green) and stock (blue) deliveries from front foot contact to ball release. Bottom: Statistical parametric mapping results for the effect of pitch length condition on vertical ground reaction force within the one-way repeated measures ANOVA. (dashed line shows the α = 0.05 threshold level for significance).

Joint moment analysis

In the previous chapter on kinematic technique parameter analysis, thoracic angle and wrist angle revealed significant changes in both discreet and continuous analysis. As there was also a shoulder angle correlation with the ball release height, which is a main predictor of ball pitch length, these three upper body joints were studied in a kinetic perspective for joint moments to find out any existing differences among the pitch length groups.

Similar to kinematic analysis, joint moments acting about the upper body interested joints were analyzed in a continuous and a discreet analysis.

Continuous analysis was done in two phases; back foot contact to front foot contact and front foot contact to ball release instance.

Continuous analysis of wrist moment

The SPM one-way repeated measures ANOVA result didn't reveal any significant differences ($p > 0.05$) in wrist moment from back foot contact to front foot contact. A significant difference was revealed ($p = 0.03$) from front foot contact to ball release for a brief period (40% - 60%) among the three variations (Figure 8.7).

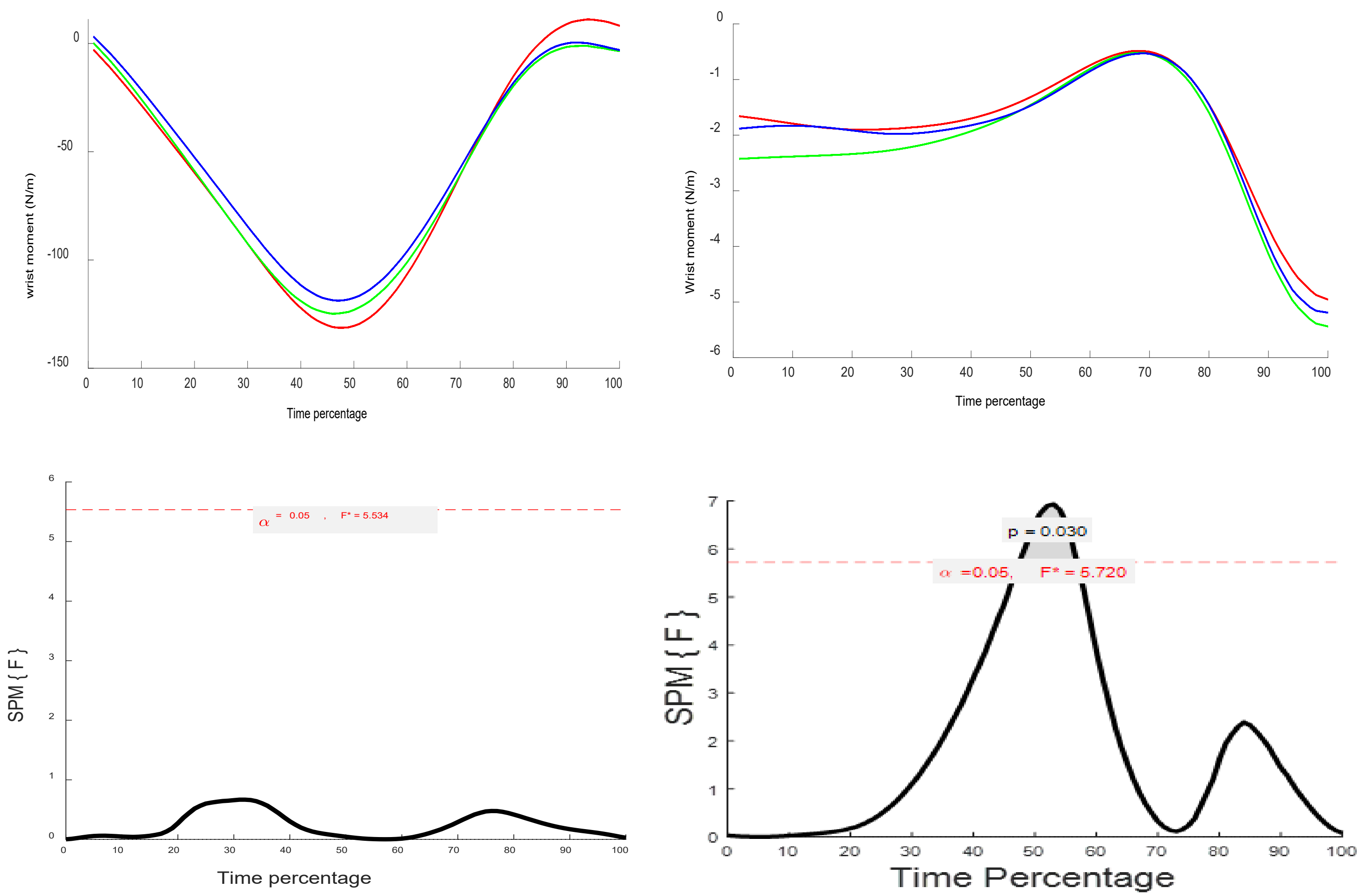


Figure 8.4: Mean normalised wrist moment from back foot contact to front foot contact (Top left) and front foot contact to ball release (Top right) for yorker (red), bouncer (green) and stock (blue) deliveries. Statistical parametric mapping results for the effect of pitch length on wrist moment within the one-way repeated measures ANOVA from back foot contact to front foot contact (bottom left) and front foot contact (bottom right).

Continuous analysis of shoulder moment

The SPM one-way repeated measures ANOVA result didn't reveal any significant differences ($p > 0.05$) in shoulder moment from back foot contact to front foot and front foot contact to ball release among the three variations (Figure 8.8).

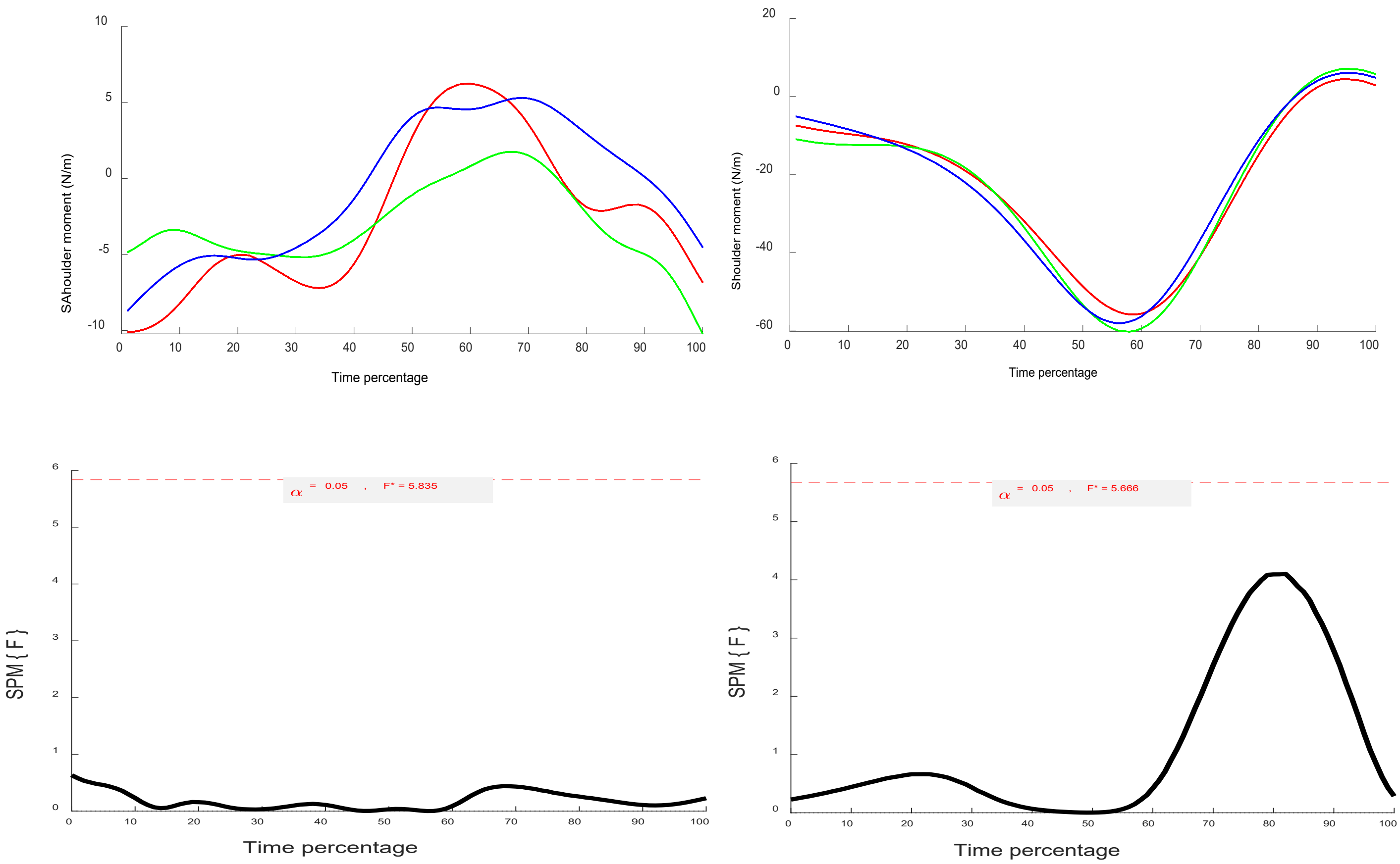


Figure 8.5: Mean normalised shoulder moment from back foot contact to front foot contact (Top left) and front foot contact to ball release (Top right) for yorker (red), bouncer (green) and stock (blue) deliveries. Statistical parametric mapping results for the effect of pitch length on shoulder moment within the one-way repeated measures ANOVA from back foot contact to front foot contact (bottom left) and front foot contact (bottom right).

Continuous analysis of thoracic moment

The SPM one-way repeated measures ANOVA result didn't reveal any significant differences ($p > 0.05$) in thoracic moment from back foot contact to front foot and front foot contact to ball release among the three variations (Figure 8.9).

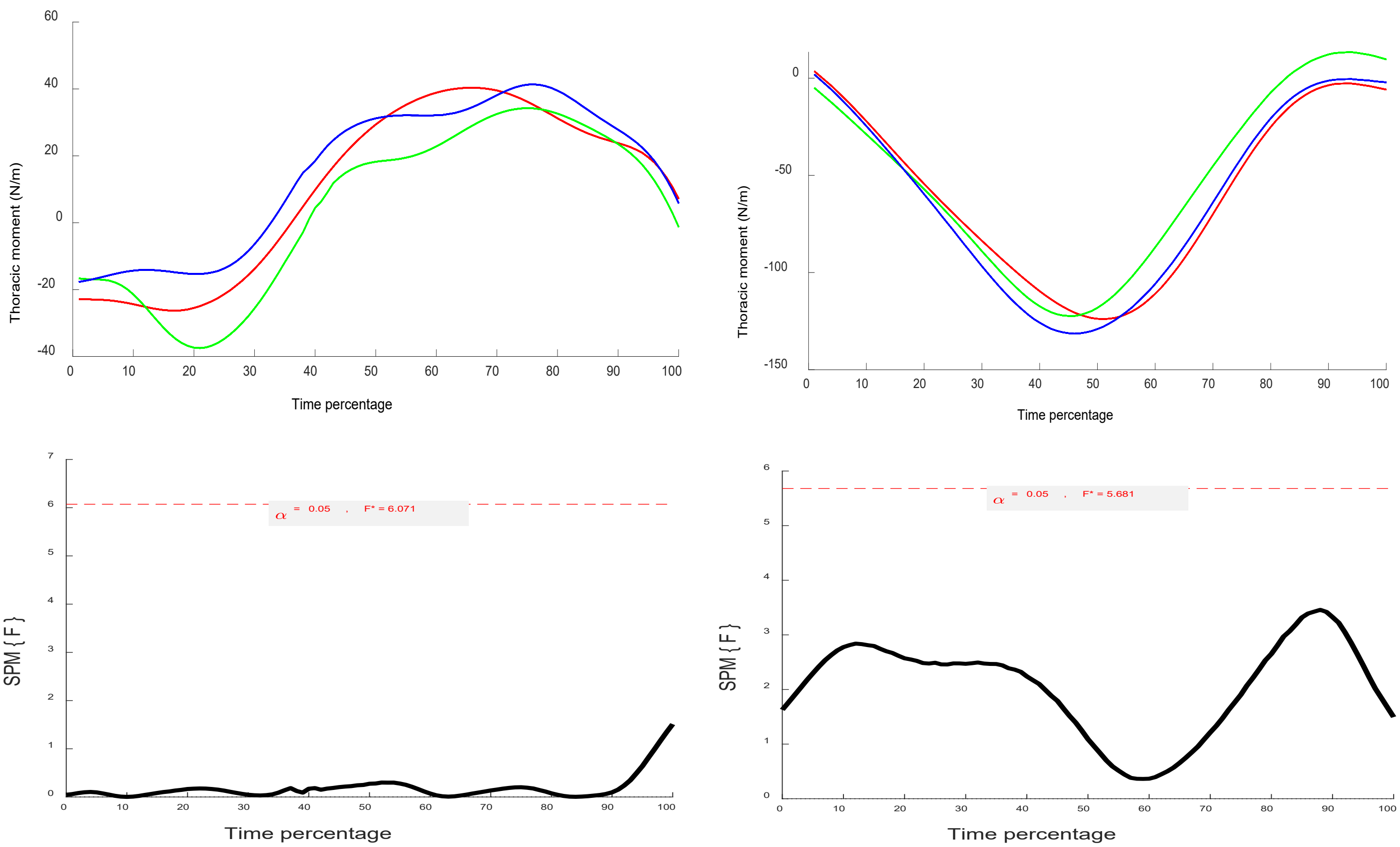


Figure 8.6: Mean normalised thoracic moment from back foot contact to front foot contact (Top left) and front foot contact to ball release (Top right) for yorker (red), bouncer (green) and stock (blue) deliveries. Statistical parametric mapping results for the effect of pitch length on thoracic moment within the one-way repeated measures ANOVA from back foot contact to front foot contact (bottom left) and front foot contact (bottom right).

Continuous analysis of wrist angular velocity

The SPM one-way repeated measures ANOVA result didn't reveal any significant differences ($p > 0.05$) in wrist angular velocity from back foot contact to front foot and front foot contact to ball release among the three variations (Figure 8.10).

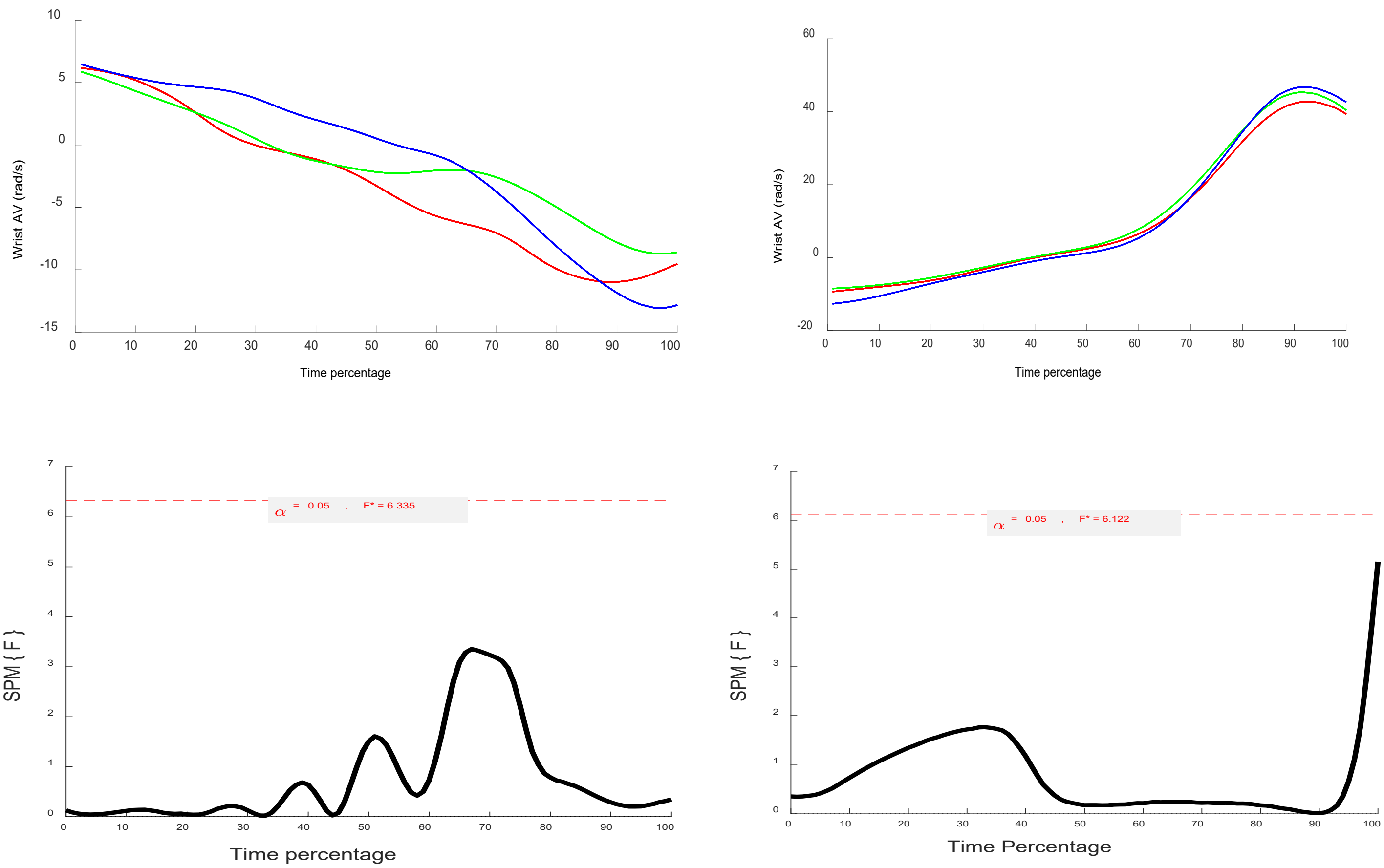


Figure 8.7: Mean normalised wrist angular velocity from back foot contact to front foot contact (Top left) and front foot contact to ball release (Top right) for yorker (red), bouncer (green) and stock (blue) deliveries. Statistical parametric mapping results for the effect of pitch length on wrist angular velocity within the one-way repeated measures ANOVA from back foot contact to front foot contact (bottom left) and front foot contact (bottom right).

Continuous analysis of shoulder angular velocity

The SPM one-way repeated measures ANOVA result didn't reveal any significant differences ($p > 0.05$) in shoulder angular velocity from back foot contact to front foot and front foot contact to ball release among the three variations (Figure 8.11).

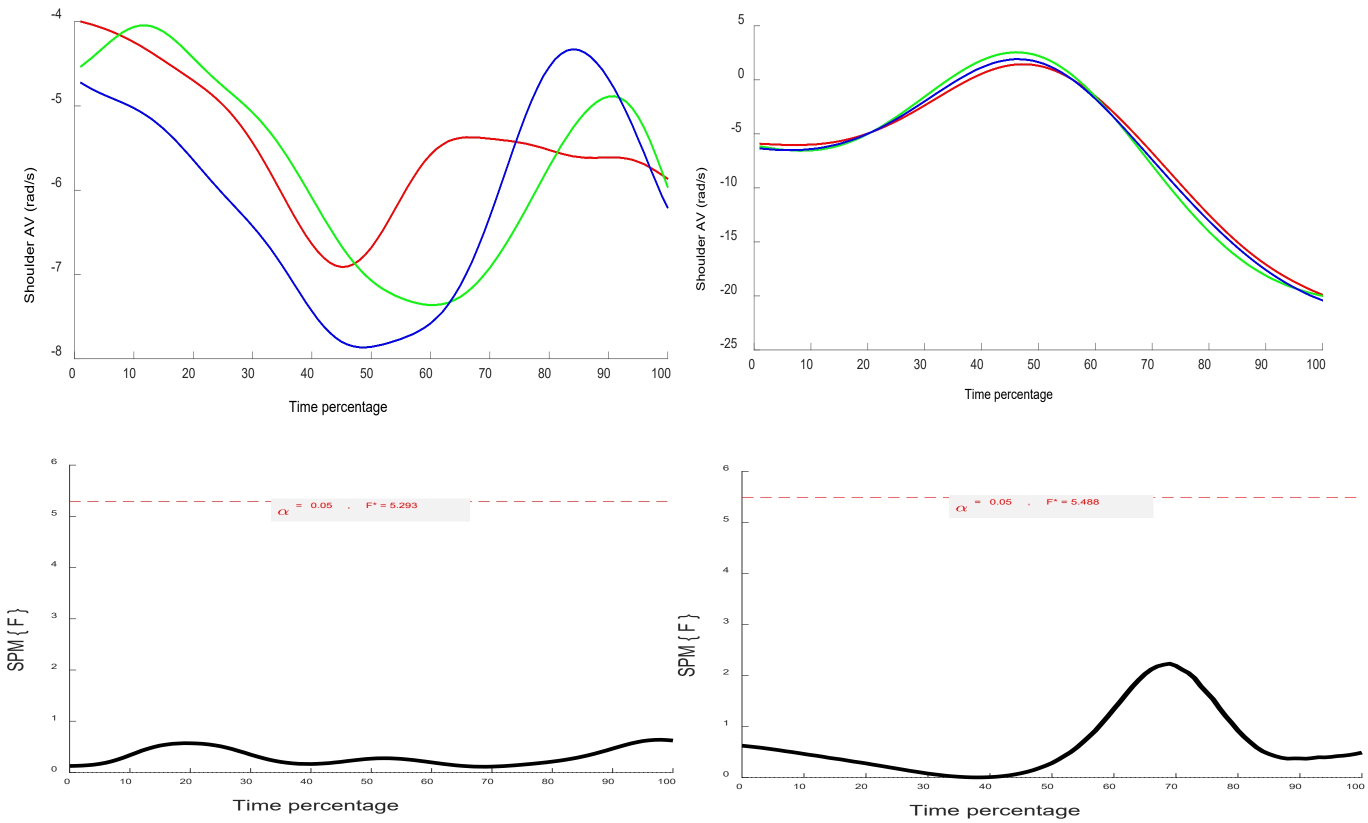


Figure 8.8: Mean normalised shoulder angular velocity from back foot contact to front foot contact (Top left) and front foot contact to ball release (Top right) for yorker (red), bouncer (green) and stock (blue) deliveries. Statistical parametric mapping results for the effect of pitch length on shoulder angular velocity within the one-way repeated measures ANOVA from back foot contact to front foot contact (bottom left) and front foot contact (bottom right).

Continuous analysis of thoracic angular velocity

The SPM one-way repeated measures ANOVA result didn’t reveal any significant differences ($p > 0.05$) in thoracic angular velocity from back foot contact to front foot and front foot contact to ball release among the three variations (Figure 8.12).

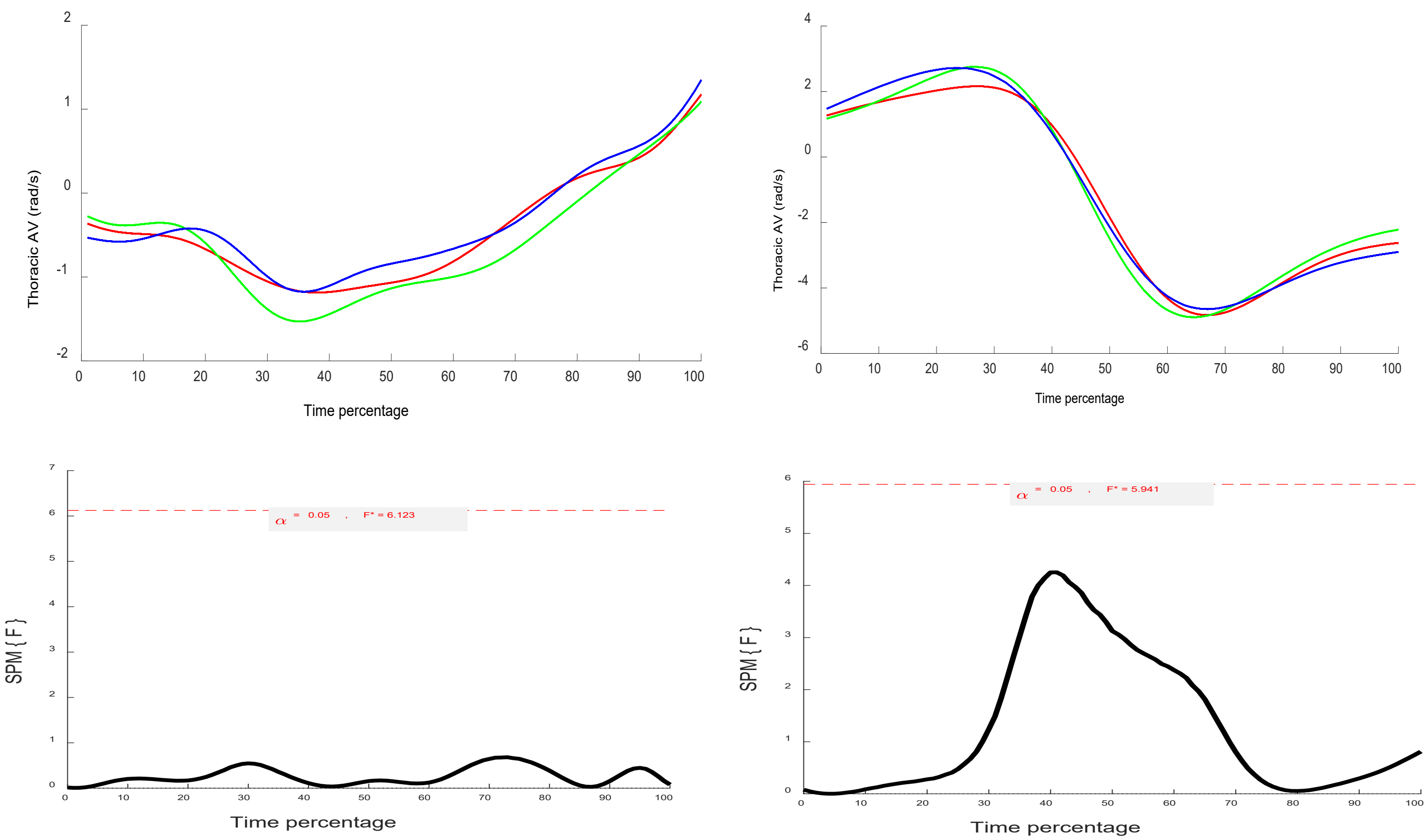


Figure 8.9: Mean normalised thoracic angular velocity from back foot contact to front foot contact (Top left) and front foot contact to ball release (Top right) for yorker (red), bouncer (green) and stock (blue) deliveries. Statistical parametric mapping results for the effect of pitch length on thoracic angular velocity within the one-way repeated measures ANOVA from back foot contact to front foot contact (bottom left) and front foot contact (bottom right).

Discrete analysis of joint moments acting on the upper body

Table 8.2: Descriptive, significance and effect sizes of the joint moments at upper extremity in fast bowling action among different pitch length groups

Parameter	yorker mean ± std (range)	bouncer mean ± std (range)	stock mean ± std (range)	ANOVA P value (multiple comparisons)	Eta squared value η^2
Wrist moment at FFC (Nm)	-1.9 ± 1.3 (-5.0– (-0.5))	-2.0 ± 1.3 (-4.8 – (-0.6))	-2.0 ± 1.4 (-4.9 – (-0.6))	0.972	0.001
Shoulder moment at FFC (Nm)	26.0 ± 12.3 (-5.0 – 52.9)	27.2 ± 14.0 (2.0 – 53.0)	28.8 ± 13.3 (-4.6 – 47.0)	0.798	0.008
Thorax moment at FFC (Nm)	9.2 ± 25.3 (-35.2 –66.7)	-4.3 ± 29.7 (-73.1 – 39.3)	-4.4 ± 29.3 (-53.3 – 46.8)	0.205	0.051
Wrist moment at BR (Nm)	-5.2 ± 1.3 (-7.7 – (3.1))	-5.3 ± 1.3 (-8.8 – (-3.6))	-5.2 ± 1.1 (-8.0 – (-3.5))	0.922	0.003
Shoulder moment at BR (Nm)	-9.5 ± 13.7 (-46.0 –12.8)	-12.9 ± 14.8 (-41.4 – 9.0)	-10.2 ± 17.7 (-42.2 – 17.8)	0.753	0.009
Thorax moment at BR (Nm)	-10.7 ± 35.5 (-63.6 –44.2)	1.2 ± 40.9 (-58.1 – 115.5)	9.4 ± 37.3 (-46.7 – 69.2)	0.233	0.047
Wrist AV at FFC ($rads^{-1}$)	-1.2 ± 1.8 (-4.9 – 1.7)	-1.3 ± 2.2 (-5.0 – 2.4)	-1.7 ± 2.1 (-5.1 – 1.2)	0.710	0.011
Shoulder AV at FFC ($rads^{-1}$)	-1.1 ± 7.5 (-15.0 – 6.9)	-3.0 ± 8.4 (-17.6 – 7.8)	-3.7 ± 7.7 (-15.8 – 6.8)	0.540	0.020
Thoracic AV at FFC ($rads^{-1}$)	1.2 ± 1.1 (-0.8 – 4.1)	1.3 ± 0.9 (-0.5 – 3.8)	1.4 ± 1.0 (-0.5 – 3.0)	0.924	0.003
Wrist AV at BR ($rads^{-1}$)	15.9 ± 4.0 (8.7 – 24.4)	12.1 ± 3.4 (3.9 – 17.5)	13.9 ± 4.1 (5.0 – 19.3)	0.009	0.146
Shoulder AV at BR ($rads^{-1}$)	17.3 ± 3.8 (11.2 – 24.0)	16.2 ± 3.3 (7.1 – 22.5)	16.5 ± 3.4 (7.4 – 22.3)	0.617	0.016
Thoracic AV at BR ($rads^{-1}$)	-2.6 ± 1.0 (-4.2 –(-0.9))	-2.7 ± 1.1 (-4.6 – (-0.2))	-2.3 ± 1.1 (-4.3 – (-0.3))	0.449	0.026

Discrete analysis of joint moments at the front foot contact and ball release phases didn’t reveal any significant differences among the pitch length groups. Bowling wrist angular velocity revealed a significant difference at the ball release instance (P = 0.009) and a large effect size ($\eta 2$ = 0.146).

This difference was not clearly identified in the continuous analysis, but Figure 8.10 (d) statistical parametric mapping revealed a significant variation at the final 10%-time duration just before the ball release which have caused the significant difference in the discrete data. Figure 8.10 (b) mean values of bowling arm angular velocities shows the significant deceleration in angular velocity of the yorker ball group just before the ball release. A reduced joint moment was acted on the wrist of the bowling arm in the middle part of the front foot to ball release phase for yorker trials (Figure 8.7 (b), (d)) which can be the reason for this angular velocity change at the ball release instance.

A stepwise regression analysis was then suggested to find out the best predictor kinetic and kinematic parameters in the upper body which could explain the Joint angle differences at ball release instance.

Wrist angle at ball release

Table 8.3: Pearson Correlation values among the interested technique parameters with wrist angle at ball release

technique parameter	correlation value (r)	Sig. (p)
wrist moment at FFC	0.566	.000
wrist moment at BR	0.039	.380
wrist angular velocity at FFC	-0.369	.001
wrist angular velocity at BR	-0.032	.401

Wrist moment at front foot contact (r = 0.566, $P < 0.05$) found to be having a positive moderate relationship with the wrist angle at ball release while wrist angular velocity had a negative weak relationship with the wrist angle (r = -0.369, $P < 0.05$).

Table 8.4: Details of the predictive equations using stepwise regression method to explain wrist angle variation at ball release

model	kinematic parameter	coefficient value	P value	explained percentage
1	Wrist moment at FFC	0.566	.000	30.9%

This regression model explains that wrist moment at front foot contact is accounted up to 30.9% of the variation of wrist angle change. As it was well explained in the continuous analysis the wrist moment changes among the groups become more significant in the middle part of the phase from front foot contact to ball release.

<u>Shoulder angle at ball release</u>

Table 8.5: Pearson Correlation values among the interested technique parameters with shoulder angle at ball release

technique parameter	correlation value (r)	Sig. (p)
shoulder moment at FFC	-0.300	.010
shoulder moment at BR	0.186	.077
shoulder angular velocity at FFC	-0.211	.053
shoulder angular velocity at BR	0.653	.000

Shoulder angular velocity at front foot contact revealed a strong positive relationship with the shoulder angle at ball release while shoulder moment had a negative weak relationship with the shoulder angle at ball release. This was very much similar to the wrist angle change explanation.

Table 8.6: Details of the predictive equations using stepwise regression method to explain Shoulder angle variation at ball release

model	kinematic parameter	coefficient value	P value	explained percentage
1	shoulder AV at BR	0.653	.000	41.7%
2	shoulder AV at BR shoulder moment at FFC	0.625 -0.220	.000 .027	45.6%

Regression model explains up to 45.6% of the change in shoulder angle at ball release by using two parameters. Shoulder angular velocity explains 41.7% change as the strongest predictive parameter while shoulder moment also increases the prediction up to 45.6%.

Thoracic angle at Ball release

Table 8.7: Pearson Correlation values among the interested technique parameters with thoracic angle at ball release

technique parameter	correlation value (r)	Sig. (p)
thoracic moment at FFC	-0.068	.300
thoracic moment at BR	-0.015	.454
thoracic angular velocity at FFC	0.431	.000
thoracic angular velocity at BR	0.047	.358

Unlike the wrist angle and shoulder angle at ball release thoracic moment didn't have a significant correlation with the thoracic angle. Only the thoracic angular velocity at ball release had a moderate relationship ($r = 0.431$, $P < 0.05$) with the thoracic angle at ball release.

Table 8.8: Details of the predictive equations using stepwise regression method to explain Thoracic angle variation at ball release

model	kinematic parameter	coefficient value	P value	explained percentage (%)
1	thoracic AV at BR	0.431	.000	17.3%

Regression model could not explain much as only thoracic angular velocity was included in the predictive model which explained the variation up to 17.3%. This explains that other than the final part just before the ball release all groups having a similar kind of a movement in the thoracic region with no additional moment involved.

8.6 Discussion

Cricket fast bowling biomechanics is mainly studied in two perspectives which are kinematics and kinetics. Although kinematic technique variables are largely discussed, some studies have stated major findings on ground reaction forces and other joint loading parameters for the performance and injury perspectives (Worthington et al., 2013; Alway et al., 2020). Most of the fast-bowling studies were finding out the important factors which enables the bowlers to release the ball faster while some have diverted to finding out different performance parameters. In this study it was intended to find out any supporting kinetic parameters involved for the changes of important kinematic technique changes when bowling different pitch length variations.

Fastest bowlers experiencing highest peak forces and loading rates in the previous studies (Portus, 2004) and latest studies has revealed that braking impulse is more important in ball release speed (Worthington, 2013). Although these studies focused on ball release speed, Callaghan et al. (2021) revealed no significant difference in loading rates and peak horizontal and vertical forces in different pitch length groups. This study accepts the same result, but a slightly lower mean peak vertical ground reaction and mean horizontal braking forces were revealed for the yorker group. These reduced forces for the yorker condition might have affected the release speeds in the group initially, although it was not intended by the bowlers. The statistical parametric mapping also revealed an almost significant value at the time of peak horizontal and vertical forces which is 20% - 30% time from the front foot contact to ball release phase.

Upper body joint kinematics were found to be the main predictor parameters for different length balls in the previous chapter. A top – down inverse dynamics method starting from the ball arm was used to calculate the joint moments acting at wrist, shoulder and thoracic- lumber joints which revealed significant kinematic changes. Wrist flexion of bowling arm was the only joint moment that revealed significant differences among the groups in the SPM (F = 5.72, p = 0.03) during the middle part of the front foot contact to ball release phase. The bouncer group was revealed to be having a greater flexion momentum than other two conditions which has caused a greater wrist flexion that was found in the previous kinematic analysis chapter. The angular velocities of the wrist didn't reveal any significance in the SPM test, but the discrete data ANOVA analysis showed a significance of angular velocity at the instance of ball release (p < 0.05). This is due to the bouncer group having the ball in hand slightly more time with a higher flexion until the ball gains a higher vertical velocity. Furthermore, the predictor model for wrist angle suggested that 30.9% change of the wrist angle at ball release could be explained by the wrist moment at front foot contact.

This can be summarized with all the previous kinematic findings mixing with this study's joint moment finding together to explain the movement of the wrist biomechanically in different pitch length trials. As the bowlers use a less extended wrist throughout the period from back foot contact to ball release instance when intending a bouncer, due to the position of the hand it will create a higher moment at wrist joint centre towards the flexion movement faster than the other two variations. This will allow the ball to be released in a lower position than other variations.

Shoulder moment and shoulder angular velocity did not reveal any significant differences but 45.6% of the shoulder angle change at ball release could be explained by the shoulder moment at front foot contact and shoulder angular velocity at ball release.

Thoracic moment and thoracic angular velocity did not reveal any significant differences and was explaining only 17.3% of the thoracic angle variation at ball release. The thoracic – lumber joint moment change can vary as the right and left shoulder moments and upper body segments causes the total moment acting on the lumber – thoracic joint. An extended thoracic angle was revealed for yorker condition than other two variations in the kinematic analysis previously and was expected to explain that change using the thoracic joint moment variations. But the slight changes of joint moments in both bowling arm and non-bowling arm changes the overall thoracic – lumbar joint flexion moments, which remained insignificant among the conditions.

As the main three joint moments (shoulder, wrist and thoracic) were investigated in a continuous study there were some inconsistencies which didn't exactly explained the changes among the conditions. Wrist joint flexion moment was expected to be significant as per the significant wrist angle revealed throughout from back foot contact to ball release in the previous chapter analysis. Although yorker balls were having a more extended position at the point of back foot contact, this change was seemed to be reducing at the point of ball release and yet the difference was significant in the kinematic analysis. This has been caused by the higher angular acceleration in wrist joint between back foot contact to ball release. Higher angular acceleration causes a greater joint torque, but the joint torque created by the weight of the hand remains lesser than bouncers and stock. Moreover, this results in an almost similar total joint moment for each of the variation, which became insignificant in the analysis. Shoulder joint moment wasn't expected as shoulder joint angle was also not significantly changed among the conditions in the kinematic analysis done previously.

8.7 Conclusion

This chapter concludes the main study which was conducted to find out the kinematic and kinetic changes of fast bowling action. This final analysis targeted the key joint moments across the different pitch length conditions during the period back foot contact to ball release. Results explained the mechanisms of the targeted wrist, shoulder and thoracic moments as the lower body joint angles and joint loadings had no significant differences among the different pitch length conditions. Although ground reaction forces didn't reveal any significant differences (same as the previous studies), smaller ground reactions were visible for yorkers. The upper body top-down joint moment analysis revealed the different forces acting on the wrist joint; that has been associated with the previously found kinematic changes at ball release. Furthermore, this chapter explains that the forces / torques are minimal for the kinematic changes found in the previous chapters.

CHAPTER 9

SUMMARY AND CONCLUSIONS

9.1 INTRODUCTION

The game of cricket consists of three main skills: batting, bowling, and fielding. Fast bowling is a technique that uses the speed of the delivery rather than spin to make it more difficult for the hitter. It consists of a series of actions that begin with the run-up and end with the follow-through after releasing the ball. The majority of studies have focused on ball release speed as a performance indicator, with kinematic and kinetic changes throughout the fast-bowling sequence being examined (Bartlett et al., 1996; Worthington et al., 2013). Fast bowlers can deceive the batter by changing the ball speed, as well as the length of the delivery, the direction of the axis, and the amount of spin. The batter may become unsettled as a result of these fluctuations, miss the ball or mishit it, which could cost them their wicket. Previous studies have looked into the differences in ball axis orientation and spin, which cause movement in the air known as "in swing" and "out swing" deliveries, and their impact on lowering batting performance (Sarpeshkar et al., 2017; Woolmer et al., 2008). There is a lack of understanding on the kinematic variables related to delivery length in cricket fast bowling, despite studies on kinetic measurements such as ground reaction force (Callaghan et al., 2021) and EMG activity of the shoulder and wrist muscles (Ahmed, 2014; Hazari, 2015). The purpose of this study was to investigate how fast bowlers varying a deliveries length using both kinematic and kinetic data and discrete / continuous analysis from back foot contact to ball release.

9.2 RESEARCH QUESTIONS AND KEY FINDINGS

1. ***How well can senior English county bowlers control the length of a delivery?***

The first aim was to identify how well fast bowlers can control the length of three common deliveries; stock, bouncer and yorker balls. Data were collected from twenty-one county level fast bowlers where each bowler performed forty-eight deliveries (twenty-four stock, twelve bouncers and twelve yorkers). An eighteen camera Vicon motion analysis system (250 Hz) was used to capture the actions with the hand marker and two ball markers labelled for each trial. 2D direct linear transformation was used to calculate the pitch length of each trial from rear camera view video recordings. Mean ± standard deviation pitch length for each delivery type were; stock 7.0 ± 3.7 m, bouncers 10.8 ± 1.4 m and, yorkers 3.8 ± 3.3 m showing that bowlers were more consistent when bowling bouncers (98.3% success rate) than stock (46.4% success rate) and yorkers (24.8% success rate). The three intended pitch lengths were used in a simple theoretical model based upon projectile motion with data from this study and the landing range between -1 and +1 SD were 5.68 m, 3.97 m and 4.21 m for yorkers, bouncers and stock balls respectively. This helped explain the large variation for yorker balls when the release was changed slightly.

2. ***Which kinematic parameters are more important in producing different length deliveries?***

The second aim of this study was to identify the main differences in release parameters between three common pitch length deliveries; yorker, bouncer, stock and to find out which technique parameters explain the differences. Previously collected data in the first study was used which was collected using twenty-one county level fast bowlers where each performed forty-eight deliveries (twelve yorkers, twelve bouncers and twenty-four stock,). An eighteen camera (MX13) Vicon motion analysis system (250 Hz) was used to capture a fifty-three-marker model specifically developed for fast bowling analysis plus two ball markers were used. 2D direct linear transformation was used to calculate the pitch length of each trial from video recordings from a rear camera view placed at the back of the run up starting position. In the study the statistical analysis (ANOVA) revealed significant differences in ball release angle and ball release height between three different variations, which led the study to conduct two separate regression analyses to find predictor variables for these parameters in each of the pitch length conditions. Wrist angle, thoracic angle, 2D hand segment orientation and the 2D thoracic segment orientation were found to be the most decisive predictor technique parameters in each of the conditions which changes the ball path after release. In addition to that a continuous analysis was done to compare kinematic technique parameters of cricket fast bowlers from back foot contact to ball release between three common pitch length deliveries. One-dimensional statistical parametric mapping analysis revealed significant differences ($p < 0.003$) between stock balls and both bouncers and yorkers in the first 30% of normalized time duration after back foot contact and a significant difference between bouncers and stock ($p < 0.002$) in the last 20% of normalised time before ball release for the thoracic angle. Furthermore, the wrist angle was significantly different ($p < 0.001$) between yorkers and bouncers from back foot contact to ball release, while stock deliveries had a significant difference compared to yorkers ($p < 0.04$) up to 90% of normalised time from back foot contact to ball release. Two-dimensional orientations of the upper arm, hand and thoracic segment also showed significant differences in continuous data between conditions.

3. ***What kinetic parameters (forces and torques) are more important in bowling different length deliveries?***

In the final study joint moments in the upper body were investigated from back foot contact to ball release using both a continuous and discrete analysis as a continuation to the kinematic findings revealed in previous chapter among the three common pitch length deliveries. Previously collected data in the first study was used which was collected using twenty-one county level fast bowlers who each performed forty-eight deliveries (twenty-four stock, twelve bouncers and twelve yorkers). An eighteen camera (MX13) Vicon motion analysis system (250 Hz) and a Kistler force plate (1000 Hz) was used to capture the actions, with a fifty-three-marker model specifically developed for fast bowling analysis plus two (tape) ball markers used. Two dimensional direct linear transformation was used to calculate the pitch length of each trial from rear camera view video recordings. A top-down inverse dynamics method was used to calculate the joint moments in the upper body joints (wrist, shoulder and thoracic). Initial repeated measures ANOVA didn't reveal ($p > 0.05$) any significant difference among the pitch length conditions for the vertical force, braking force and loading rates. The continuous analyses also didn't show any significant differences, but yorker balls revealed reduced vertical and braking forces from front foot contact to ball release compared with bouncers and stock deliveries. Although, one-dimensional statistical parametric mapping analysis reported significant changes ($p = 0.03$) in wrist moments for bouncers between front foot contact to ball release for a brief period (40% - 60% duration) it was not significant at the ball release instance. A lower angular velocity of the wrist was revealed in bouncers at the start of front foot contact to ball release, but it could not explain the small wrist moment change among the conditions as the angular velocity differences was not significant in the one-dimensional statistical parametric mapping analysis. Although shoulder moment and shoulder angular velocity explained up to 45.3% of the shoulder angle change at the ball release instance, the regression models couldn't explain the changes of wrist angle and thoracic angle change which were significant at the ball release instance in the previous kinematic analysis.

9.3 STRENGTHS AND LIMITATIONS

1) Understanding the most difficult variation to be executed.

   The study investigated how successful the bowlers were at bowling different length variations. Surprisingly the succession rate for yorker balls was considerably lower (24.8% vs 46.4% and 98.3%). Also, previous studies have shown that the teams which bowled more yorkers were more successful in winning matches (Justham et al., 2008).

   Therefore, one of the major understanding was that although yorkers are more important in winning matches, the bowlers were unable to repeat it when they were asked to. Identifying the most successful bowler in repeating the same yorker length during training would be an advantage as they will be attacked during the match if they were missing the length continuously. This can be one of the major strengths in this study which shows the importance of finding the most successful bowler who can pitch the ball in the yorker area which is harder for the batter to score.

   From a practical perspective, there were some limitations during the data collection as there was not an actual batter present and the bowler was not in the same psychological condition where he or she might be in a match situation. The pitching length accuracy when it comes to a yorker can improve or sometimes reduce depending on that.

2) Upper body kinematic changes which are most important in producing different variations

   A key strength of this study is the findings regarding the kinematic differences across fast bowling variations. The importance of the finger 2D orientation at the point of ball release was established as one of the new identifications in this study which was significantly different among the pitch length conditions. As it was found out that ball release angle and ball release height percentage were significantly different in each pitch length condition, separate regressions revealed it was the wrist angle, thoracic angle, 2D hand segment and 2D thoracic segment orientation were the main technique parameters responsible from 31% to 89% in different pitch length conditions for the changes in both release angle and release height percentage which ultimately influences the pitch length.

From a coaching perspective finger orientation is one thing which is coachable where the player can be asked to feel the ball till the last moment where a lower angle with the horizontal level could be achieved which supports ball release angle. Although the angles are not coachable the players and coaches can concentrate on this in training when bowling specific variations. In addition to that thoracic angle control in bowling bouncers and yorkers could be focused on for a better outcome. Although bowling bouncers and yorkers is done in practices there is not specific guidelines on how to bowl these variations other than hitting on the correct length. These findings in the study can help the coaches and players to adapt to certain movements before bowling the expected variation.

Although clear findings were revealed, an actual batter in the experimental set-up might have increased the accuracy of some bowlers (more realistic) as they tend to land the predetermined variations in the expected area when there is a batter. Additionally, the lack of bounce in the artificial cricket pitch might have led the bowlers to change their length as they are expecting a higher bounce in a normal pitch. Moreover, the theoretical calculation revealed the importance of very slight changes in the ball release resulting in large pitch length differences. Therefore, if the data had been captured at a higher frequency, the accuracy of the release instance might have been improved and that may have helped identify additional factors linked to pitch length.

9.4 FURTHER RESEARCH

A previous study (Worthington, 2013) has revealed the importance of thoracic flexion to ball release speed and this study identified thoracic flexion as one of the main predictors of ball release angle which ultimately produces bouncer balls when the thoracic flexion is higher. Therefore, a further investigation would reveal any connection among these parameters.

Moreover, this thesis provided an initial exploration into different pitch length bowling variations as one of fast bowling's performance parameters in the current game of cricket. Since the players were selected without any action classification criterion, this would be a great starting point for the future studies to investigate for the same kinematic and kinetic changes in all four actions according to Portus (2004).

9.5 OVERALL CONCLUSION

In conclusion, fast bowlers were found to have significantly different kinematic and kinetic parameter values when attempting to bowl different pitch length deliveries. Initially, bowlers found it difficult to land the ball in the expected area for yorker balls compared to stock and bouncers. 2D finger orientation of the bowling hand, 2D thoracic orientation, thoracic angler and 2D shoulder orientation at the ball release were the key kinematic changes which explained the change of pitch length in the initial analysis. Continuous analysis revealed significant changes in wrist angle specifically from the back foot contact until the ball release among the variations in addition to the changes found in the discrete analysis. Vertical and braking forces remained insignificant as per the previous studies. Wrist moment of bouncers showed a significant change from 40% - 60% duration during the back foot contact to ball release instance, but it was insignificant at the ball release instance. Although regression models contained kinematic predictor variables could explain the changes, regression models which contained kinetic variables couldn't explain much on changes of ball release angle or ball release height. Further studies need to examine the possible kinematic variables in different fast bowling actions for a better understanding key changes among the different pitch lengths.

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APPENDIX 1 - Players consent form

Loughborough University

A Biomechanical Analysis of Fast Bowling Variations

INFORMED CONSENT FORM

(to be completed after Participant Information Sheet has been read)

Taking Part	**Please initial to confirm agreement**
The purpose and details of this study have been explained to me. I understand that this study is designed to further scientific knowledge and that all procedures have been approved by the Loughborough University Ethics Approvals (Human Participants) Sub-Committee.	----------------------
I have read and understood the information sheet and this consent form.	----------------------
I have had an opportunity to ask questions about my participation.	----------------------
I understand that taking part in the project will involve being video recorded.	----------------------
I understand that the personal information collected will be name, DoB, height and weight.	----------------------

I understand that I am under no obligation to take part in the study, have the right to withdraw from this study at any stage for any reason, and will not be required to explain my reasons for withdrawing.	**----------------------**
<u>Use of Information</u>	
I understand that all the personal information I provide will be processed in accordance with data protection legislation on the public task basis and will be treated in strict confidence unless (under the statutory obligations of the agencies which the researchers are working with), it is judged that confidentiality will have to be breached for the safety of the participant or others or for audit by regulatory authorities.	**----------------------**
I understand that personal information collected about me that can identify me, such as my name or video, will be available to and can be retained by my coaches.	**----------------------**
I agree that information I provide can be quoted anonymously in research outputs.	**----------------------**
<u>Consent to Participate</u>	
I voluntarily agree to take part in this study.	**----------------------**

_______________________________ ___________________________ __________

Name of participant [printed] Signature Date

_________________________________ _____________________________ ___________

Researcher [printed] Signature Date

Appendix 2 - Participant information form

Loughborough University

A Biomechanical Analysis of Fast Bowling Variations

Adult Participant Information Sheet

Investigators Details:

Kaushal Manawadu, Loughborough University, Epinal way, Loughborough, LE11 3TU, K.P.Manawadu@lboro.ac.uk

Professor Mark King, Loughborough University, Epinal way, Loughborough, LE11 3TU, M.A.King@lboro.ac.uk

What is the purpose of the study?

The purpose of this study is to understand what affects fast bowling performance.

Who is doing this research and why?

This study is part of a Student research project. The main investigator, Kaushal Manawadu, will be leading the study, supervised by Professor Mark King.

What will I be asked to do?

This study involves a few areas of data collection, you will be asked to complete the following:

- Up to 8 overs of fast bowling deliveries.
- Anthropometric measures to be taken.

Where are the sessions and how long will it take?

You will be asked to attend one session at the FAR lab in the NCSEM, where motion capture and force data will be recorded of your bowling action (60 mins) and anthropometric measurements (20 mins). Please wear tight fitting clothing (eg. Shorts).

I'm not sure I want to participate.

Participation in this study is voluntary and if you decide to not take part it will not be detrimental towards you. After you have read this information and asked any questions you may have, if you are happy to participate, we will ask you to complete an Informed Consent Form. However, if at any time, before, during or after the sessions you wish to withdraw from the study please contact the main investigator.

However, once the results of the study are collected and the thesis has been submitted (expected to be by June 2023), it may not be possible to withdraw your individual data from the research.

Data Protection Privacy Notice

Loughborough University will be using information/data from you in order to undertake this study. Your coaches will have access to and be responsible for looking after your personal information and using it appropriately.

What personal information will be collected from me?

Name, gender, height and weight will be collected from all bowlers along with video footage, force plate and motion capture data of your bowling.

Will my taking part in this study be kept confidential?

Yes. All information presented in the final thesis will be anonymised. Only your coaches will be able to access your personal information and data. All personalised data will be stored on a system with login credential requirements and double factor authentication.

How will the data collected from me be used?

Results of this study will be used in the final thesis write-up, however all data will be anonymous. Your personal data can be used by your coaches to aid your performance improvement.

What is the legal basis for processing the data?

Personal data will be processed on the public task basis.

Individuals' rights to erasure and data portability do not apply if you are processing on the basis of public task. However, individuals do have a right to object.

Under the General Data Protection Regulation (GDPR), some of the personal data which will be collected from you is categorised as "sensitive data". The processing of this data is necessary for scientific research in accordance with safeguards. This means that study has gone through an ethical committee to ensure that the appropriate safeguards are put in place with respect to the use of your personal data.

Will my data be shared with others?

Your data will only be shared with the study investigators, your coaches and support staff if approved by you.

How long will the anonymised data/samples be retained?

We will keep identifiable personal information about you for 5 years after the study has finished (approximately June 2028).

I have some more questions; who should I contact?

Kaushal Manawadu K.P.Manawadu@lboro.ac.uk

If you have any questions more generally regarding Data Protection at the University, then please do contact the Data Protection Officer on dp@lboro.ac.uk or write to The

Data Protection Officer at Academic Registry, Loughborough University, Loughborough, Leics, UK LE11 3TU.

What if I am not happy with how the research was conducted?

If you are not happy with how the research was conducted, please contact the Secretary of the Ethics Approvals (Human Participants) Sub-Committee, Research Office, Hazlerigg Building, Loughborough University, Epinal Way, Loughborough, LE11 3TU. Tel: 01509 222423. Email: researchpolicy@lboro.ac.uk

The University also has policies relating to Research Misconduct and Whistle Blowing which are available online at http://www.lboro.ac.uk/committees/ethics-approvals-human-participants/additionalinformation/codesofpractice/ .

If you have taken steps to have a concern or complaint about Loughborough University's handling of data resolved but are still not satisfied you have a right to lodge a complaint with the Information Commissioner's Office (ico), who are the relevant regulator for data privacy and protection matters. The ico can be contacted at Wycliffe House, Water Lane, Wilmslow, SK9 5AF and your will find more information at https://ico.org.uk.

Appendix 3 – Subject details

Subject	Test Date	Height	Weight
01	10/2020	1.861	74.5
02	10/2020	1.836	78.5
03	10/2020	1.989	86.9
04	10/2020	1.858	93.7
05	10/2020	1.821	72.8
06	10/2020	1.911	80.45
07	10/2020	1.8	74.7
08	12/2020	1.777	73.45
09	12/2020	1.872	65.05
10	11/2020	1.894	74.4
11	11/2020	1.918	85.8
12	12/2020	1.895	85.05
13	11/2020	1.867	78.7
14	11/2020	1.828	89.1
15	11/2020	1.888	90.3
16	11/2020	1.781	81.45
17	12/2020	1.835	70.4
18	11/2020	1.851	90
19	11/2020	1.907	80.8
20	11/2020	1.928	108.65
21	11/2020	1.873	74.5

Appendix 4: Anthropometric Proforma

ANTHROPOMETRIC MEASUREMENTS FOR SEGMENTAL INERTIA PARAMETERS

NAME [ ] AGE [ ] DATE [ ]

All measurements in millimetres

TORSO

Level	hip	umbilicus	ribcage	nipple	shoulder	neck	→	nose	ear	top
Length	0						0			
Perimeter										
Width										
Depth										

LEFT ARM

Level	shoulder	midarm	elbow	forearm	wrist	→	thumb	knuckle	nails
Length	0					0			
Perimeter									
Width									

RIGHT ARM

Level	shoulder	midarm	elbow	forearm	wrist	→	thumb	knuckle	nails
Length	0					0			
Perimeter									
Width									

LEFT LEG

Level	hip	crotch	midthigh	knee	calf	ankle	→	heel	arch	ball	nails
Length	0						0				
Perimeter											
Width											
Depth											

RIGHT LEG

Level	hip	crotch	midthigh	knee	calf	ankle	→	heel	arch	ball	nails
Length	0						0				
Perimeter											
Width											
Depth											

Height (m) [ ] Mass (Kg) [ ]