Biomechanical Assessment of Pitch Length Control and Kinematic Variability in Cricket Fast Bowling

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1.0 Student Declaration and Ethics Declaration

"I, Alan Sutherland, declare that the Master of Research thesis entitled 'Biomechanical assessment of pitch length control and kinematic variability in cricket fast bowling' is no more than 50,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work".

"I have conducted my research in alignment with the Australian Code for the Responsible Conduct of Research and Victoria University's Higher Degree by Research Policy and Procedures.

Ethics Declaration

"All research procedures reported in the thesis were approved by the Loughborough University Ethical Advisory Committee, PROJECT ID: 3156, Proposal 2021-3156-2596."

Signature [redacted] Date 26/07/2022

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4.0 Glossary of Abbreviations

ASIS – Anterior superior iliac spine

BFC - Back foot contact

BR - Ball release

Dof - Degrees of Freedom

FFC - Front foot contact

H_{RP} - Horizontal release position

HV_{BR} - Horizontal ball release velocity

IoC - Index of Cooperation

LCS - Laboratory Coordinate System

Mid - Mid-acceleration phase

MPJC - Metatarsal phalangeal joint centre

PCS - Pitch Coordinate System

PSIS – Posterior superior iliac spine

Py – Horizontal release position (abbreviation for H_{RP} used in ball flight prediction models)

Pz – Vertical release position (abbreviation for V_{RP} used in ball flight prediction models)

SCS - Somatic Coordinate System

S_WBEV - Simulated whole-body effector variability

V_{RP} - Vertical release position

VV_{BR} - Vertical ball release velocity

Vy – Horizontal release velocity (abbreviation for HV_{BR} used in ball flight prediction models)

Vz – Vertical release velocity (abbreviation for VV_{BR} used in ball flight prediction models)

WBEV - Whole-body effector variability

3MPJ – Third metacarpal phalangeal joint

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6.0 Abstract

Cricket fast bowling coaches have an abundance of knowledge related to speed production and bowling technique. However, bowling coaches find large gaps of research knowledge related to bowling accuracy. While a consistent pitch length (accuracy) can be achieved from a redundant combination of four ball projection parameters (horizontal velocity, vertical velocity, horizontal position, and vertical position), there is no current research of these relationships. Furthermore, the link between body position and ball projection is unknown. While gait studies have employed kinematic effector units to explain functional biomechanics and control of stance and swing limbs of walking, this type of analysis is rare in sports biomechanics. This motivated this study to divide the whole-body into three effector units (Leg, Trunk and Arm) to analyse how body position effects bowling accuracy. This study aimed to provide preliminary information related to the research gap of the general nature of three-dimensional body position variability and bowling accuracy through investigating pitch length control.

A group of 12 sub-elite male fast bowlers volunteered to be biomechanically tested on their performance of 18 good length bowling trials. Ball and body kinematics were captured from a three-dimensional motion analysis capture system (250 Hz) setup at an indoor cricket pitch. Each bowler's set of BR and body effector variables were represented as mean and standard deviation from 18 trials. Ball pitch length was determined via a flight prediction model based on constant acceleration.

A multi-linear regression analysis showed that the four release parameters accounted for 79% of pitch length variability, where vertical velocity variability accounted for the greatest variability (90%). A coordinated covariance test did not find any redundant cooperation among the four BR parameters. Therefore, pitch length accuracy appears to be achieved by independent control of vertical velocity.

Three-dimensional body effector position vectors were time-normalised to the acceleration phase of bowling (FFC to BR) and presented in each dimension as time-waveform signals. The average variance of the effector profile during the bowling phase was calculated across each bowler's 18 trials and 11 time-slices. A stepwise linear regression analysis found that variance in Leg-X and Trunk-Z effectors can explain 85% of the variance in vertical velocity variability at BR. A coordination covariance test also revealed that redundant coordination of body effector position exists in the X- and Z-dimension. In summary, the ball vertical velocity at BR is the critical parameter that determines pitch length control, while dimension-relevant variability of the Leg effector and Trunk effector determine vertical velocity variability.

In summary, this project identified valuable preliminary information that can readily be translated and applied to coaching methods for bowling accuracy. Furthermore, it offers sound insights for future research to enquire deeper into the nature of fast bowling accuracy.

7.0 Background

In a cricket match, the bowler's ability to release the ball at high speed is a major weapon for dismissing batters. This is because ball speed reduces the batter's available reaction time, which can force them into error. This is the desired outcome for a fast bowler. However, fast bowlers also need to control ball landing accuracy to not only constrain a batter's selection of shots, but it further increases the batter's uncertainty and stroke error. Indeed, being proficient in both accuracy and speed is seen as a competitive advantage that plays an important role in a strategic fast bowling plan (Gray et al., 2003; Feros et al., 2018). The coaching of fast bowling development in emerging talent is focused on both of these performance objectives. However, bowling speed fills a major proportion of the research literature, while in contrast, the research into accuracy is limited. This is likely due to pitch length control being dependent upon a complex trade-off between four properties at BR (i) horizontal velocity (anterior posterior direction), (ii) vertical velocity (superior inferior direction), (iii) vertical release position and (iv) horizontal release position. Furthermore, the gain in knowledge brought about by the investigation of release velocity and release position requires a different methodological approach than that which adopted when solely investigating speed. BR position requires an analysis of kinematic variability (and co-variability), while ball speed requires an analysis of energy transfer optimisation. An appropriate analysis of kinematic variability requires an experimental design that obtains a sufficiently large set of bowling trials, where the participants pursue a consistent task goal. This is demanding for both the participants and the investigators. Hence, knowledge of bowling accuracy from biomechanical studies is limited.

Biomechanical investigations of bowling technique, relevant to ball speed, have typically identified critical features based on an average characteristic gleaned from several trials. Indeed, this can be useful for developing a biomechanical model to simulate bowling speed, and therefore provide an optimisation analysis of contributing factors. However, these biomechanical models treat the system in modular components that express a central tendency of states, while the nature of variability (and co-variability) inherent to the body kinematics is often overlooked due to the lack of model sensitivity. The collective trade-off between the four release parameters leads to bowling accuracy requiring control and coordination of a redundant dynamical system (of multiple DoF). In principle, the body control system aims to stabilise the most goal relevant DoF. Indeed, in addition to the collective goal of length control, there may also exist other over-arching goal priorities, such as speed, safety (i.e., musculoskeletal stress) or energy minimisation (i.e., muscle work). Ultimately, the nature of variability within the system, and how it is structured, will be affected by the over-arching task goal/priority. Understanding the nature and structure of variability in the bowling action is important for coaches, so as to identify the responsible sources and mechanisms that may underlie bowler length control.

From a dynamical systems perspective, movement variability is considered to serve as an important function for the flexible transition between movement patterns, and for attaining stable control within a movement pattern (Van Emmerik et al., 2005; Yang et al., 2007). In general, stability and flexibility are features of a dynamical system that is composed of multiple redundant components, or agents. The whole-body action of fast bowlers is an example of such a system, where multiple segment linkages expand from foot to opposite hand (also known as an effector system), where the position and velocity of the endpoint of the kinetic chain (i.e., end-effector and ball) expresses the task goal of the bowler. The kinetic link principle also describes this process as a proximal to distal transfer of energy across multiple body segments (Marshall & Elliott, 2000; Ferdinands et al., 2013). This is initiated by a large external force from the ground through the front/lead leg, proceeding to generate end-effector velocity, whereas the hand at BR is the last segment that expresses the final release properties determining ball accuracy, such as position and velocity (Ferdinands et al., 2013). During this large energy transfer, there will likely be significant kinematic perturbations throughout the segment chain that could require flexible and stable organisation to control the collective kinematic elements to achieve the desired properties of BR. By requesting bowlers to repeat consistent task goals (i.e., equivalent release properties), we can investigate the nature of kinematic variability that underlies length control.

Kinematic variability can be investigated from different methods. Van Emmerik et al. (2016) has expressed variability as either end-point variability (i.e., performance variability, commonly pertaining to the end-effector) and coordinative variability (i.e., task variability, or variability within an effector system). End-point variability is referred to as the variability in the task goal expressed by a vector that defines the kinematic span of the effector system (i.e., position, velocity), while coordinative variability is referred to as variability within the kinematic parameters (i.e., joint angle) (Van Emmerik et al., 2016). Redundancy can exist between multiple effector systems that cooperate on a collective task goal, or within the elements of a single effector system (i.e., segments that contribute to the lower limb effector chain). Redundancy in the bowling action means there is a broad repertoire of kinematic configurations that can achieve an equivalent outcome. Skill adaptation through redundancy is thought to be represented by two processes (Yang et al., 2007). Firstly, kinematic equilibrium is thought to be established at endpoint because of the changes in coordinative variability (Yang et al., 2007). Secondly, kinematic arrangements in the action that do not directly affect endpoint trajectory can find new solutions (Yang et al., 2007). This means as bowlers practice accuracy there is a broad set of solutions, but as they become more proficient their end-effector is thought to become more reliable. This, in turn, results in a reduction of variable solutions, yet multiple pathways still exist to produce the same end-effector, such as hand position at BR remaining stable (Yang et al., 2007). This is the type of conceptual framework that is adopted to investigate kinematic variability in fast bowling.

8.0 Aims

This research aims to investigate how kinematic effector variability and BR properties influence pitch length control in cricket fast bowling. To explore this topic, this thesis sought to answer this over-arching aim by addressing four areas of enquiry, whereby each set of questions is a progressive step forwards to uncovering new layers of understanding.

1. **Which ball release parameter (or combination of parameters) is/are most responsible for determining pitch length variability (accuracy)? Do sub-elite fast bowlers coordinate the four projection parameters?**

There are redundant solutions among the four BR parameters that equivalently achieve the same pitch length. It is hypothesised that fast bowlers are able to co-adapt between these parameters to achieve an accurate pitch length.

2. **What is the nature (time, dimension) of effector system variability?**

Body effector position variability is hypothesised to be transient throughout the bowling action. This aim seeks to explore how each effector's variability compares to each other during the acceleration phase and BR event, and whether some effector units or dimensions are inherently more variable than others.

3. **What elemental effector or effectors, and in which dimension, explain the most critical release parameter towards pitch length control?**

This research question aims to identify a model of effector variability, through which variability of elemental effector components can explain the variability of the most critical release parameter towards pitch length control. It is hypothesised that there will be a model of effector variability that will influence release parameter variability.

4. **Is there evidence of inter-effector cooperation to control whole-body posture?**

The fourth aim is to explore redundancy of the effector system and if inter-effector cooperation is occurring to control whole-body effector variability (i.e., body posture). It is hypothesised that inter-effector cooperation is occurring to control whole-body effector variability throughout the acceleration phase.

9.0 Literature Review

A deterministic model of the contributing mechanisms that underlie pitch length accuracy provides a contextual framework to explore the research literature on cricket bowling. This model shows that pitch length is dependent upon four release properties, which are, horizontal velocity, vertical velocity, vertical release position and horizontal release position. These are not mutually exclusive, though. Therefore, for a bowler to bowl accurately they need to control each of these four release factors. However, within each factor more sub-factors determine the result. The sub-factors that contribute to two-dimensional velocity are different to those that contribute to two-dimensional release position. Body posture is a result of three effector vector systems and each system will contribute to the whole in a different way. The variability and coordination between these three systems will result in the release position (and whole-body effector) and, therefore, play its role in accuracy.

Movement variability within the action arises from external and internal sources, such as ground reaction forces (Glazier & Worthington, 2014) and muscle torque motion-effects (Ferdinands et al., 2014). Fast bowling invokes large sources of error due to large external forces and large muscle forces. The effects of variability will not be equivalent for each effector system of the body, and nor for the three release properties.

Technique analysis studies of cricket bowling use a biomechanics approach, which dominates much of the literature. The studies of technique can be generally split into two themes: general bowling technique and ball release speed. A review of technique's relationship to ball release speed, cricket fast bowling accuracy, ball release position, ball release position coordinated covariance and kinematic variability was conducted via a non-systematic review of the literature.

9.1 Technique analysis for speed and injury

Technique-based studies have identified key parameters of a bowling action and their impact on speed production, within several main temporal phases and events. Identified phases have included the run-up, pre-delivery stride (also known as the `bound'), delivery stride and follow through (Olivier et al., 2016). On the other hand, common event stages have included back foot contact (BFC), front foot contact (FFC) and ball release (BR) (Ferdinands et al., 2010). These event stages are used to define where parameters are recorded and have also been used to distinguish between different time phases of the action. By splitting the action into specific phases, it allows researchers to ascertain which mechanisms and parameters contribute to sub-task goals within each phase. The run-up phase is defined within the start of the bowler's approach to the initial moment of take-off for the pre-delivery stride (Glazier & Wheat, 2014). This phase enables fast bowlers to build up centre of mass velocities (Ferdinands et al., 2010). The pre-delivery stride is marked by the delivery stride take off and ends at back foot contact (Glazier & Wheat, 2014). Back foot contact event then defines the start of the delivery stride phase and back foot contact sub phase, as it is the first critical bowling event that marks where the bowling action takes place (Ranson et al., 2008). Front foot contact then follows back foot contact and defines the start of the second sub-phase of the delivery stride, the FFC sub-phase (i.e., acceleration phase). This sub-phase has been identified as an important phase to describe speed production. For instance, at BR, front knee angle during this phase has been linked to bowler's release speed, as the braced leg acts as a breaking force enabling efficient transference of linear momentum (Portus et al., 2004), by providing a stable lower body that can be used as an effective lever (Wormgoor et al., 2010). The follow through is the final phase of the bowling action and it occurs directly after ball release, but it has no bearing on speed or accuracy (Glazier & Wheat, 2014).

Further analysis of bowling technique within these phases and events, has meant researchers have been able to critically identify biomechanical factors that contribute to ball release speed. As a result, a significant amount of research has focused on understanding this relationship (Glazier et al., 2000; Portus et al., 2004; Worthington et al., 2013a; Middleton et al., 2016). Salter et al. (2007) reported in a group of male bowlers, that ball release speed was related to a number of variables, including centre of mass velocity at back foot contact and stride length from back foot contact to front foot contact. Methodologically, Glazier et al. (2000) and Portus et al. (2004) both adopted linear correlation methods to determine whether ball release speed was independently linked with parameters of technique. However, by using a regression analysis method, Worthington et al. (2013a) identified a group of independent variables that explained 74% of the variance for ball release speed. These variables included: run-up speed; knee angle at ball release; upper trunk flexion from FFC to BR events; and shoulder angle at front foot contact (Worthington et al., 2013a). Therefore, analysis of key events and phases has substantially aided the exploration of knowledge on ball release speed production in cricket fast bowling.

Technique analysis studies within key events and phases have also been important to understand injury risk in bowling. Certain bowling techniques and parameters have been found to be associated with increased likelihood of injury (Portus et al., 2004). Bowling technique has been traditionally classified according to trunk-pelvis orientation to define side-on, front-on, semi-open and mixed bowling actions (Ferdinands et al., 2010). Portus et al. (2004) used this method to classify bowling technique, with the side-on action thought to have a back foot contact angle of greater than 240 degrees. The semi-open action is defined as having a back foot contact shoulder angle of between 240 and 210 degrees, while the side-on action has a back foot contact shoulder angle of less than 210 degrees (Portus et al., 2004). All these three actions experience less than 30 degrees of movement in shoulder counter-rotation and back foot contact pelvis-shoulder separation angle (Portus et al., 2004). The mixed action on the other hand can be defined solely by the pelvis-shoulder separation angle and or shoulder counter-rotation angle, as it demonstrates larger degrees of movement than do the other three actions (Ferdinands et al., 2014). Portus et al. (2004) classifies it as having greater than 30 degrees of movement in either shoulder counter-rotation and back foot contact pelvic-shoulder separation. It is also the most common technique used, but evidence suggests it is associated with the greatest risk of lower back injuries (Portus et al., 2004). Shoulder counter-rotation injuries are also common in mixed action bowlers and were found to be just as prevalent in females as men (Stuelcken et al., 2008). Injured female fast bowlers exhibited less external rotation range of motion in their bowling arm compared to non-injured bowlers (Stuelcken et al., 2008). But inter-variation effector motion or joint motion was not assessed, nor addressed in relation to ball release speed or accuracy in these papers. This is consistent with most bowling injury analyses, as assessment of technique-related intrinsic factors including kinematics and kinetics have found to be lacking (Olivier et al., 2016).

9.2 <u>Accuracy and pitch length control in cricket fast bowling</u>

Research on accuracy and pitch length control in comparison to speed and technique has seen significantly less research. While accuracy is a more complex property of bowling to assess, it is nevertheless still surprising to find limited studies on this, due to the obvious performance advantages gleaned from it. Pitch length accuracy refers to the ability of the bowler to achieve a predetermined target via the fast bowlers intended ball flight trajectory (McNamara et al., 2015). Pitch length control refers to the ability of the bowler to replicate their pitch length accuracy consistently. Therefore, for the purpose of this study, pitch length accuracy and pitch length control refer to the same objective outcome.

In general, research data on accuracy has been recorded as a secondary aim to larger studies. This included looking at the effect of pitch length on performance in junior fast bowlers (Harwood et al., 2018) and the effects of dehydration on performance (Devlin et al., 2001). However, when investigating technique factors on performance Portus et al. (2000) noted a possible correlation between shoulder counter-rotation and accuracy. But this relationship is yet to be fully explored, as most accuracy-based or pitch length-based articles have not attempted to analyse the association between coordinative movement patterns of technique and the outcome of accuracy (Glazier & Wheat, 2014). This has also been the case in other projectile sports like baseball, whereby limited attention has been used to understand accuracy (Kawamura et al., 2017). An article by Phillips et al. (2012) examined how accuracy was affected by the pitch length (task goal) amongst a skill-diverse group of male pace bowlers. It was believed that more skilled players were better able to adapt their action to meet the task goals (Phillips et al., 2012). However, the role of kinematic variability was not explored in this study because no kinematic data was included. Phillips et al. (2012) did note there was a lack of knowledge on the influence of task goals on kinematic task variables. However, after ten years, no studies since have directly addressed the relationship between accuracy and kinematic variability within the bowling action.

To assess bowling accuracy, research has followed a couple of different methodological approaches to determine a bowler's performance. It may be split into one whole or separate groups of line and length. Length control has been a major focus in the literature because analysing bowling line faces more external variables that influence line, such as swing and seem movement. Thus, investigating ball pitch length is seen as less externally influenced dependent measure. To investigate length, research has adopted two different methodological approaches in determining its accuracy. The most common approach is to set up a screen with target areas behind or in line with the batter's stumps, with a scoring zone allocated per area of interest (i.e., Phillips et al., 2012 & Portus et al., 2000). The bowler is requested to bowl at the target and is scored on their consistency to hit that area. This approach is believed to be more specific to match day outcomes as it assesses where the ball passes the batter and equates to how bowlers will assess their on-field performance during a game (Portus et al., 2000). However, this approach may not be transferable necessarily from a laboratory environment to match day, as the differing bounce conditions of the pitch and ball could influence the pitch location to which the bowler bowls. For instance, even when the ball is pitched within the desired area, the ball and wicket itself may act in an undesirable way and result in a poorer outcome and so may a synthetic surface of the laboratory give differing results to turf pitches. The second approach adopted by researchers is to record where the ball has landed on the pitch in relation to the batter's end. Cork et al. (2012) used this approach where they calculated the pitch location in reference to the middle stump. A benefit of this method is that it takes away the inconsistencies of the differing wicket conditions and bounce variability that may affect the overall accuracy of the delivery after it bounces. The results can then either be scored by using a similar grid system or by taking an average and standard deviation result from the pitch cluster. Recording the cluster or pitch map would allow for greater assessment of associations between kinematic parameters and variability with accuracy, as it will be easier to determine the mechanics of the action to achieve that pitch grouping and pitch length variability.

When assessing pitch length control not all bowlers will bowl the same length as bowler's natural good length can vary between each bowler. Some are naturally fuller, while others tend to bowl a bit shorter, which is considered to be back of a length. However, as the bowlers are freely able to bowl their own personal good length, the group average had to match existing length values considered appropriate for an overall good length. A literature review conducted by Harwood et al. (2019) found a good length appeared to pitch approximately 6 m from the batter's stumps, with 6.15 m being associated with good performance. However, other studies have stated differing good length classifications. Ball and Hrysomallis (2012) noted a good length was between 3.8 – 5.8 m from the batter's stumps, while Sarpeshkar et al. (2017) stated a value between 7.0 – 8.0 m, therefore an appropriate group mean and median range for good pitch length deliveries was deemed, for the purposes of this study, to be somewhere between 4.0 – 8.0 m.

9.3 Ball release position and ball release parameter coordinated covariance

Along with accuracy to date, cricket literature has largely overlooked how bowlers reliably achieve a consistent ball release position. Release height (i.e., vertical release position) has been recorded quite extensively in the literature, yet medio-lateral release positioning and anterior-posterior (i.e., horizontal release) positioning has not been so thoroughly reported. There are only a handful of articles recording the ball release position in at least two dimensions and each have used differing coordinate reference systems to determine the location. Cork et al. (2012) used an external reference system at the base of the middle stump to define the three-dimensional release position at the crease. In contrast, Harwood et al. (2018) adopted an internal reference system by defining the ball release position as an individual percentage of player height and release distance from the front foot. To date, Harwood et al. (2018) is the only study that has investigated individual variability of ball release positioning in two-dimensions. This latter method is preferred for inter-participant measures, because it establishes the correct initial kinematic conditions to compare consistency between participants, due to height and technique differences. For analysis of release parameter control and flight predictions, a standard external reference system is required however, to ascertain standard initial conditions needed for such analysis.

Despite reporting on ball release position not being a priority in many fast-bowling biomechanical studies, it still plays an important role in the ball's pitch length location. That is because a combination of vertical release position and horizontal release position is the initial condition at which the ball is projected from. Along with longitudinal and vertical ball release velocities (i.e., speed), each play a vital role in determining pitch length from the projected flight. However, the interplay between these four variables in describing pitch length and the bowler's ability to control these to achieve a consistent pitch length is not well known. To investigate release positioning's role, it needs to be taken from an external reference system similar to that used by Cork et al., (2012). However, the variability of release parameter control needs to be looked at from an internal reference system, as not only is the front foot landing position variable (external), but the horizontal release position is also variable within bowlers (Harwood et al., 2018). Yet, to this date there has been no cricket bowling research conducted on how these four variables are interrelated, nor have there been investigations to determine how the bowler is trying to control them.

The relationship between inter-related release parameters has been addressed in other sports and motor activities. For instance, in baseball pitching coordinated covariance (or compensatory coordination) of ball release parameters has been investigated recently and shown promising signs in uncovering whether release parameters are controlled and adapted to maintain vertical displacement (Kusafuka et al., 2022). It is known these release parameter values vary widely between baseball pitchers (Nagami et al., 2011) and it could be expected that the same applies for cricket fast bowlers, as there are numerous combinations (i.e., redundancy) of initial conditions (i.e., release parameters) that can result in the same pitch length. Therefore, if a combination satisfies the goal outcome of a desired pitch length, a bowler can select a varied range of such ball release parameters to achieve that outcome. Coordinated co-variance of release parameters that contributes to performance stability has been shown in non-complex two-dimensional movements (Kudo et al., 2000; Nasu et al., 2014) and with constrained virtual tasks (Müller and Loosch, 1999; Scholz and Schöner, 1999; Cohen and Sternad, 2012). Accuracy analysis in tennis serves also indicated accuracy performance is decreased when variability is increased in the linear speed in both the longitudinal and vertical axes (Antúnez et al., 2012). Thus, it could be theorised that a bowler who has greater control over their release parameter selection will produce a better performance outcome overall.

9.4 Ball release parameter reproducibility

However, reproducibility of release parameters could also be assistive at improving goal related outcomes and not all parameters may be equally important. For many sports, the improvement of reproducibility of end-point location (accuracy) is a desired goal, whether that be kicking, hitting, or throwing. As stated earlier, there are numerous combinations (i.e., variability) of release parameter variables present within the release parameter system. This inherit variability for each parameter and control is necessary to actualise the performance goal (i.e., pitch length accuracy), as not all parameters may be weighted equally. Kusafuka et al. (2022) found that baseball pitching accuracy was mainly caused by variation in pitching angle and a deviation of several degrees would produce significant changes in pitch location, more so than with other release parameters. Notably, Kusafuka et al. (2022) also found little indication of coordinated co-variation improving accuracy in baseball pitching. Rather, vertical displacement was likely improved by reproducibility (i.e., reduction of variability) of pitching angle (Kusafuka et al., 2022). Reproducibility has also been shown to be more significantly linked to performance and provides a larger room for improvement than release parameter coordination in basketball free-throws (Nakano et al., 2022).

9.5 <u>The nature of kinematic variability and influence on task outcomes</u>

There exist different theories on how motor variability affects task outcomes, and this variability can be expressed in different forms. Variability arises from perturbations in noise from external and internal sources (Mehdizadeh & Glazier, 2021). However, to investigate variability, the right data analysis approaches are necessary to distinguish between kinematic variability and noise (Glazier, 2011). Measurement noise comes from errors acquired from data acquisition and acts separately, and in addition to, the signal representing movement dynamics (Van Emmerik et al., 2005). Noise has normally been interpreted as a limitation when measuring kinematic variability and should be removed or reduced (Glazier, 2011). However, kinematic variability may not be a result of unwanted noise and should not be overlooked (Glazier, 2011). As such there is scope for researchers to understand this association and its respective contribution to task outcomes (Glazier, 2011).

Van Emmerik et al. (2016) has expressed variability as either kinematic variability (i.e., performance variability, end-point variability) and task variability (i.e., coordinative variability). Kinematic variability is referred to as the variability in the task goal expressed by a vector that defines the kinematic span of the effector system (i.e., position, velocity), while task variability is referred to as variability within the kinematic parameters (i.e.,joint angle) (Van Emmerik et al., 2016). Therefore, kinematic variability refers to variability in the whole system (effector) and task variability refers to the variability within the kinematic parameters of that effector. Task variability influences task outcomes by allowing for flexible transitioning between known fundamental patterns and newly learnt movement patterns, through transference of instability between key parameters that define them (Antúnez et al., 2012). However, task and kinematic variability could also act as an expression of numerous systems and is the immediate impact of degrees of freedom (DoF) associated with the movement (Antúnez et al., 2012). Degrees of freedom falls under the principle of redundancy or abundance (Latash, 2012). It is a principle that observes many non-utilised adaption task variables, that are normally in surplus without elimination; yet are still utilised to help stabilise the specific task performance (Latash, 2018). However, within the DoF of the motor system there remains both good and bad variability that can affect the performance outcome (Wu & Latash, 2014). Elite performers, for instance, can move through these abundant degrees of freedom and utilise the good variability within to ensure consistency of performance outcomes. Glanzer et al. (2019) noted in baseball pitchers a significant correlation between pitch location and task variability; and baseball pitchers have shown the ability to correct their action throughout their throw (Fleisig et al., 2017). This motor control correction has also been identified in golf swings, with expert performers being better able to utilise a greater sub-set of their abundant degrees of freedom compared to beginners (Morrison et al., 2016). Thus, having control over good task and kinematic variability of the fast-bowling action should theoretically lead to a consistent (i.e., stable) ball release position (i.e., task goal).

9.6 Kinematic variability in cricket fast bowling

The time-course of kinematic variability and how it contributes to body posture control at ball release (i.e., task goal) is not well understood in fast bowling. This is because intra-subject kinematic variability has received limited attention in cricket literature (Harwood et al., 2018), with only a handful of studies addressing the topic of task and/or kinematic variability in bowling biomechanics. All of these variability studies conducted analyses on kinematic differences in technique parameters (almost exclusively inter-participant variability) in relation to task goals of bowling different lengths (Callaghan et al., 2019), impacts of a prolonged spell (Schaefer et al., 2018) and on ball release speed (Salter et al., 2007). However, Salter et al. (2007) and Schaefer et al. (2018) also conducted an intra-variability analysis on their subjects. Salter et al. (2007) found a greater standard deviation in variability between participants than between trials. However, only one bowler was assessed for intra-participant variability across twenty trials. Callaghan et al. (2019) indicated an overall consistency with parameters throughout a spell and suggested there was no significant change between task variables and delivery length. However, these articles all used standard deviation to explain kinematic variability for both inter- and intra-participant analyses. Traditionally, the variance is quantified by the standard deviation measure. However, changes in standard deviation across a measure cannot identify the source of these changes (Rosenblatt et al., 2014). By using standard deviation, the focus is taken away from demonstrating how bowlers were able to adjust their action, instead focusing on showing an average response for the average bowler (Glazier & Wheat, 2014). Therefore, these cricket variability studies were unable to adequately explain the deeper nature of kinematic variability. This issue has led researchers towards adopting a combined approach of quantifying both the average fluctuations and dynamic fluctuations in movements, and the dynamical systems theory approach (Van Emmerik et al., 2016), as well as an engineering approach related to optimal feedback control theory (Diedrichsen et al., 2010).

This thesis adopts a dynamical systems theory perspective to interpret results about the relationship and understanding of variability, stability and redundancy. The embodied human motor control system manages a complex neuro-musculo-skeletal apparatus. The challenge of movement stability and flexibility of critical biomechanical states impressively emerges from the control over an abundance of many degrees of freedom (Van Emmerik et al., 2016). For dynamical system theorists, movement variability can represent a diverse set of flexible solutions to meet a task goal, rather than an indication of unwanted noise (Cazzola et al., 2016). For instance, bowlers have shown large standard deviations in knee flexion at front foot contact (Callaghan et al., 2019), however, it is unknown whether this variability is good or bad for performance. For example, it could be assumed that the knee joint is adapting flexibly to mitigate force perturbations experienced by the bowler’s front leg, and potentially large knee angle variations might be task beneficial. Latash et al. (2018) supports the views of Bernstein (1967), who first proposed that motor abundance and its control is critical for the human motor system perform stable, flexible and precise movements. This is the perspective taken for this study, where variability is the compound effect from a control strategy that aims to simultaneously mitigate and exploit external and internal noise, and motor abundance, for a functional purpose.

9.7 Concluding statement

Despite significant research being conducted on technique and BR speed, the relationship between kinematic variability and release properties to pitch length control remains as an unfilled knowledge gap in cricket fast bowling literature. To address bowling control, the research design herein considers methods that examine evidence of flexible coordinated body state adaptations. Phillips et al. (2012) noted that kinematic cooperation between task goals and task variables lacks sufficient investigation in cricket bowling. Thus, this thesis proposes to adopt analysis techniques to assess variability of the kinematic effector systems considered to be relevant to the collective task goal of whole-body position. However, to explore pitch length control, this study also needs to investigate the influence of the four BR parameters and the interplay between them (coordinated covariance), to correctly inform bowler consistency. Exploring the variability and cooperation between BR parameters and their influence on bowler length control will further knowledge regarding cricket bowling accuracy and the general requirements of cricket fast bowling.

10.0 Methods

10.1 Methodology and conceptual framework

The methodology and conceptual framework of this thesis will be a cross-sectional study design guided by a post-positivist, quantitative analysis structure from biomechanical measurements. It aims to empirically investigate how BR properties contribute to pitch length accuracy, and how variability of body segments and limbs (effectors) contribute to these BR properties. A post-positivist paradigm is adopted to evaluate numerical data that represents the ball landing accuracy and kinematic variability of cricket bowling (Creswell & Creswell, 2018). Empirical data was gathered from a biomechanics experiment design, which is conceptualised by a deterministic model (Figure 10.7.3.1). This model of bowling accuracy was used to determine how underlying mechanisms and goals contribute to the overall performance goal. The results of this investigation will be interpreted through a Dynamical Systems Theory paradigm, where movement variability as considered an important attribute for both flexible and stable movement patterns (Van Emmerik et al., 2005; Yang et al., 2007). In context of this theoretical paradigm, this thesis aims to explore redundant components of BR parameters and body position. This study explored four inter-dependent research questions, where each subsequent research question draws upon results found from preceding aims.

10.2 Ethics approval

Human research ethics approval for this project was provided by Loughborough University (PROJECT ID: 3156). Data collection was conducted at Loughborough University. An agreement between Victoria University Human Research Ethics Committee and Loughborough University was established to enable data sharing. The author of this project was included as a principal contributor on the Loughborough University ethics application.

10.3 Subjects

Twelve male fast bowlers (mean ± standard deviation: age 19 ± 1; height 1.87 ± 0.04 m; body mass 82.4 ± 11.5 kg) volunteered to participate in this investigation. Ten of the bowlers were right-handed while the other two were left-handed. All bowlers though were current members of the Marylebone Cricket Club University squad and have been scouted for potential first-class cricket representation, which is correct for too individuals amongst the bowling cohort. Bowlers were identified as 'fast bowlers' by Marylebone Cricket Club University and county academy fast bowling coaches. Project information and testing procedures were explained to the bowlers prior to data collection, in accordance with the guidelines set by the Loughborough University Ethical Advisory Committee.

10.4 Data collection procedure and experimental protocol

10.4.1 Data set-up

Kinematic data was collected at Loughborough University at their indoor cricket facility. This was an appropriately large facility fitted with a standard artificial turf pitch, which allowed the bowlers to bowl with their full run-up. The cricket pitch had a regulation length of 20.12m as per the laws of cricket. A landing mat was secured at the batter's end of the pitch, with horizontal lines spanning the width of the pitch (at two-meter intervals between the bowling and batting creases). The bowling crease was positioned on the edge of two adjacent force platforms. Surrounding the bowler's end of the pitch were an array of 18 Vicon cameras to capture the bowler's full delivery stride (from the pre-delivery stride to the two strides post BR). A competition standard cricket ball was used in all trials (mass of 156 g).

10.4.2 Marker set-up

A three-dimensional biomechanical model of the bowler and ball was reconstructed from position-time data of the three-dimensional coordinates from a full-body marker set-up. Each participant was fitted with forty-seven 14 mm retro-reflective markers attached over selected anatomical bony landmarks, as specified by Worthington et al. (2013b) (Figure 10.4.2.1). Each cricket ball had two retro-reflective markers (15 x 15 mm reflective patch) attached to each hemisphere of the ball, representing an axis that was orthogonal to the spinning motion of the ball's seam.

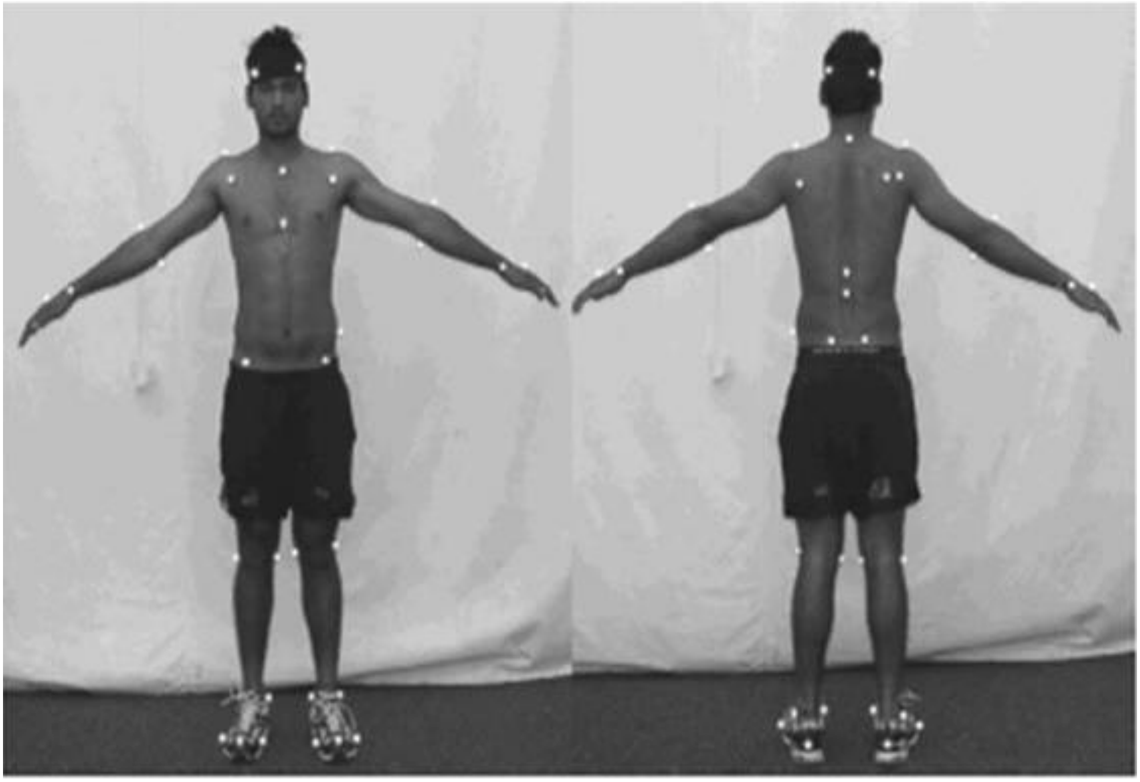

Figure 10.4.2.1: *Minimal marker set-up convention applied in this study and previously used for fast bowling biomechanical model reconstruction by Worthington et al. (2013b).*

10.4.3 Data collection protocol

All participants underwent a thorough warm-up prior to data collection. To standardise the trial results to each participant's normal standing posture, each participant performed a standing trial prior to the bowling trials. This calibration trial was used to calculate the reference pose of each body segment and spine as per Ranson et al. (2008). Each bowler then bowled eight, six ball overs split into four sets of two overs (i.e., 48 trials). Each two-over set was pre-set in order of three good length trials followed by a yorker, bouncer, and then yorker, followed then by an additional three good length trials, a bouncer, yorker and bouncer. In total, twenty-four trials were bowled at a target length considered by the individual bowler to be 'a good length', while twelve trials were bowled at both a full length ('yorker') and a short length ('bouncer'), again deemed length appropriate by the bowler. Differences in pitch length are described below in Figure 10.4.3.1. If a bowler was unable to bowl the requested forty-eight trials, they were asked to bowl twenty-four on a good length, and six each on a full and short length. All bowlers were given the goal of reproducing their match-day speed and effort to simulate competition performance conditions. Bowlers also used a self-selected rest period between each trial and following each set of twelve trials a 5-minute rest period was given.

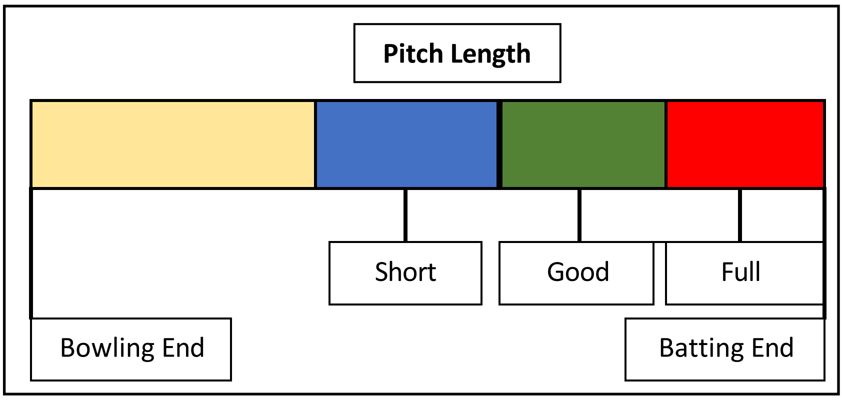

Figure 10.4.3.1: Example of pitch length classifications.

10.4.4 Instrumentation

Kinematic data was measured by an 18 camera (MX13) Vicon camera system (OMG PLC, Oxford, UK) operating at a capture rate of 250 Hz. Kinetic data was measured by two adjacent Kistler force platforms (900 x 600 mm, Type 9287B, Winterthur, Switzerland) operating at a sampling rate of 1008 Hz. The two force platforms were secured to ground rails located beneath the landing mat at the bowling crease. The platforms were covered with a 25 mm layer of artificial grass and level with the pitch surface.

10.5 <u>Data processing</u>

Labelling was conducted in Vicon Nexus 2.10.3, whereby all trials were labelled, and appropriately gap filled. The Nexus ‘rigid fill’ process was used to fill gaps when an occluded marker was associated with adjacent intra-segment markers. All gap-filled position-time data processed from Nexus were then exported as *.c3d format for further processing in Visual3D (C-Motion Pty, Germantown, MD, USA). A biomechanical model was reconstructed and assigned to marker trajectories of all bowling trials (Figure 10.5.1 represents the reconstructed bowling model). Each segment coordinate system was defined from a combination of at least three markers placed at anatomical landmarks representing segment endpoints.

A fourth order low pass Butterworth filter with a 15 Hz cut-off was used to filter position-time data of the body markers. The 15 Hz cut-off has been adopted in similar biomechanical studies that have assessed kinematics in cricket fast bowling (Bayne et al., 2016) and in baseball pitching (Kobayashi et al., 2016; Solomito et al., 2020). However, to accurately identify the BR event from first derivative of ball position-time data, the ball markers were not filtered. This decision was based on work by Worthington et al. (2013a).

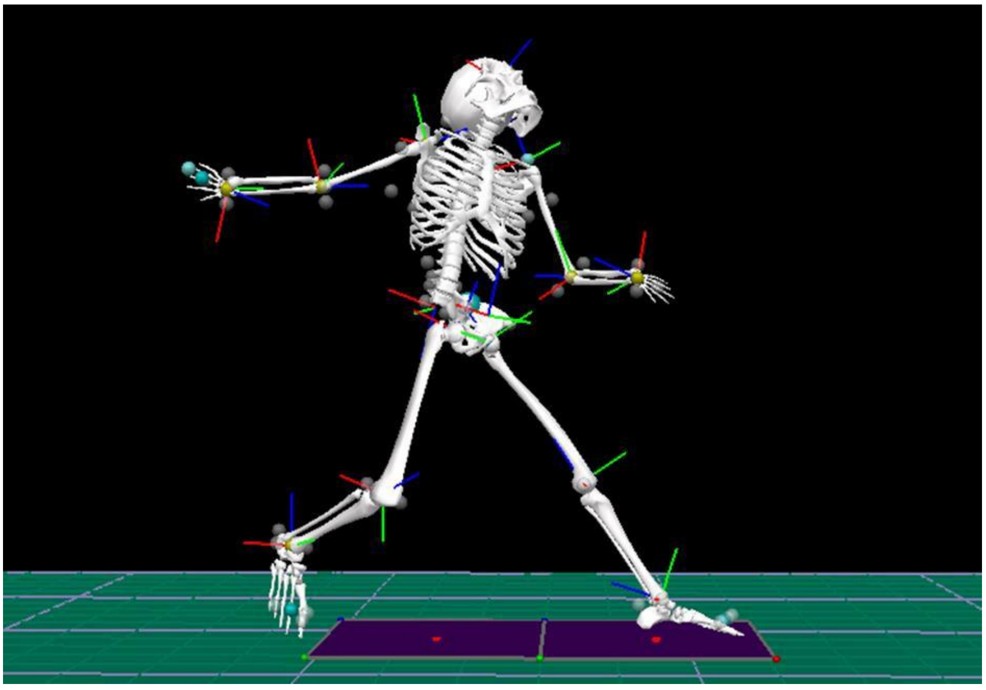

Figure 10.5.1: *Reconstructed model of the bowling action in Visual3D.*

10.5.1 Body model

This section outlines the definitions of the biomechanical model reconstructed from the marker set to create an inter-subject consistent three-dimensional skeletal system for kinematic analysis.

10.5.1.1 Calibration landmarks and segment endpoints

Metacarpal phalangeal joint: represented by the 3rd metacarpal phalangeal joint.

Wrist: The wrist axis and joint centre was identified by the midpoint between two markers at the distal forearm (medial wrist was represented by the styloid process marker and the lateral wrist was represented by the styloid process of the radius).

Elbow: The elbow axis and joint centre was identified by the midpoint between the markers located at the lateral and medial epicondyles of the proximal humerus.

Shoulder: A medial distance of 0.1 m from the lateral shoulder marker created a virtual marker to identify the glenohumeral joint centre.

Hip: A virtual marker was created in Visual3D by using their regression equation common to the CODA pelvis model. The regression equation uses the anatomical locations of the markers at the left and right ASIS (Anterior Superior Iliac Spine) and markers at the left and right PSIS (Posterior Superior Iliac Spine).

Knee: The knee joint axis and centre was defined by the midpoint between the lateral and medial epicondyles of the distal femur.

Ankle: The ankle axis and joint centre was defined by the midpoint between the lateral and medial malleolus at the distal fibula and tibia.

Metatarsal phalangeal joint: represented by the 2nd metatarsal phalangeal joint marker.

10.5.2 Segment coordinate systems

Body segment anthropometrics were created in Visual3D (C-Motion Inc, USA) based on segment endpoints described above. A segment coordinate system was established using conventional XYZ reference system recommended for model reconstruction in Visual3D, using three or four segment endpoint markers (calibration markers) to create an anatomically relevant orthogonal coordinate system. The hand and foot segments were tracked using a six degrees-of-freedom least-squares best fit convention; however, the shank, thigh, pelvis, trunk, upper arm and forearm segment pose was tracked using Visual3D kinematic fit optimisation tool to minimise the soft-tissue effects on the shoulder and hip joint kinematics.

Foot CS: Positive Z-axis from 2nd metatarsal phalangeal joint centre to the ankle joint centre. Positive Y-axis was orthogonal to the plane defined by four markers at the segment endpoints (i.e., 1st and 5th Metatarsal phalangeal joint and medial and lateral ankle markers).

Shank CS: Positive Z-axis from ankle joint centre to the knee joint centre. Positive Y-axis was orthogonal to the plane defined by four markers at the segment endpoints (i.e., medial, and lateral ankle Malleolus and knee Epicondyle markers).

Thigh CS: Positive Z-axis from knee joint centre to the hip joint centre. Positive Y-axis was orthogonal to the plane defined by three markers at the segment endpoints (knee epicondyles and virtual hip joint).

Pelvis CS: Defined by using the anatomical locations of the left and right anterior and posterior superior iliac spine. The positive Z-axis was orthogonal to the plane fitted to the four PSIS and ASIS markers. The positive Y-axis was directed from the left and right midpoints between PSIS to ASIS.

Head CS: Defined by using four left and right anterior and posterior head markers. The positive Z-axis was orthogonal to the plane fitted to the four markers. The positive Y-axis was directed from the left and right midpoints between posterior to anterior.

Thorax CS: Positive Z-axis from midpoint between left and right posterior superior iliac spine (i.e., sacrum) and the midpoint between the left and shoulder joint centre. Positive Y-axis was orthogonal to the plane defined by two PSIS markers and two left and right virtual shoulder joint markers.

Upper Arm CS: Positive Z-axis from shoulder joint centre to the elbow joint centre. Positive Y-axis was orthogonal to the plane defined by three markers at the segment endpoints (virtual shoulder joint and calibration markers at the elbow).

Forearm CS: Positive Z-axis from elbow joint centre to the wrist joint centre. Positive Y-axis was orthogonal to the plane defined by four calibration markers at the segment endpoints (medial and lateral elbow and wrist).

Hand CS: Positive Z-axis from wrist joint centre to the third metacarpal joint. Positive Y-axis was orthogonal to the plane defined by three markers at the medial and lateral wrist and 3rd metacarpal phalangeal joint.

10.5.3 Ball model

The centre position of the ball (Ball_1M) was determined by a virtual midpoint marker that was created between two tracking markers placed at the diameter of the ball's axis of spin/rotation.

10.6 Coordinate systems:

Lab coordinate system (LCS): Origin and axis aligned with the corner and physical dimensions of the force platform. A calibration wand with a set of retro-reflective markers was placed at the back left corner of the force platform, and the positive Z-axis was orthogonal to the plane created by the wand markers. The Y-axis and X-axis were aligned with the edge dimensions of the force platform.

Pitch coordinate system (PCS): Origin at the base of the middle stump at the bowling crease, while the positive Y-axis was directed down the long axis of the pitch, from middle stump of the bowling crease to middle stump at the batting crease. The pitch coordinate system was used to define BR position and the calculation of ball pitch position.

Somatic coordinate system (SCS): A body reference system was created for deriving inter-subject consistent parameters. The origin of the somatic coordinate system was positioned at the metatarsal phalangeal joint centre (MPJC) of the front foot when at the BR event. The directions of the SCS X-, Y-, Z-axis were congruent and aligned with the PCS.

10.7 Data analysis

Analysis of key time events of the bowling trial was conducted in Visual3D. These events separated the task into two major phases: balance (BFC to FFC) and acceleration phase (FFC to BR).

10.7.1 Event identification

Back foot contact (BFC): Using the second derivative of the back foot ankle marker, the local minimum of the ankle Y-axis acceleration (i.e., maximum deceleration event) was identified as the event when BFC occurred. This method was verified as valid from mis-trials when a bowler's t landed cleanly upon the first force platform.

Front foot contact (FFC): Identified as the frame in when the vertical ground reaction force that was applied to the front landing foot first exceeded 50N.

Mid acceleration phase (MID): Value at the half-way point of the FFC to BR acceleration phase. Taken at the midpoint (50%) in time between the FFC event and BR event.

Ball release (BR): The first visual frame where the distance between landmark Ball_1M exceeds 50 mm of forward separation of distance from the virtual landmark Ball_CT. Concluded as an appropriate measure to obtain BR after conducting a sensitivity analysis and comparison to another commonly adopted BR method (see Section 10.10)

10.7.2 Phase identification

Preparation Phase: Identified as the time between the BFC and FFC events. This phase generally captures the moment where the bowler is readying themselves for front footcontact and the transfer of kinetic energy.

Acceleration Phase (FFC-BR): Identified as the time between FFC to BR. This phase has also been called the delivery phase by (Ranson et al., 2008). This phase captures the energy transfer through the body and the arm acceleration to BR.

10.7.3 Trial inclusionary criteria

Pitch Length Analysis: All trials that were bowled at top-of-off (good length trials) were initially included in the analysis. Trials included in the pitch length analysis were valid if the position trajectories of the hand and ball markers were captured or reliably gap filled for minimum of 10 frames before and after the BR event. A second criteria was that the mathematically estimated pitch position was also within 3 m of the visually observed pitch length. If there was no 3 m agreement between the methods, it was assumed that a marker tracking error had occurred, and the trial was rejected from further analysis. The mean and standard deviation of all the good length trials were then recorded, and a Grubbs' Test was adopted to identify trial outliers. The first 18 trials that satisfied this criterion were used in the final analysis.

Effector Analysis: The trials included in this analysis needed to satisfy the pitch length analysis criteria and have a clean FFC on the force platform

Pitch length:

To determine predicted pitch length accuracy, it was first necessary to consider the elements acting on the ball at BR and their contributing influencing factors. To do this a deterministic model was adopted to outline key elemental release factors the bowler produces to bowl a delivery. Factors outlined in the deterministic model (Figure 10.7.3.1) are what will be explored in determining their variability and influence on pitch length accuracy. Pitch length accuracy was thought to be predominantly influenced by two factors, two-dimensional release position and two-dimensional release velocity. Within each of those factors were two further elemental inputs (release parameters) of horizontal and vertical, release position and velocity respectively. These four release parameters were considered influential mechanical release components that the bowler needs to control or adapt to achieve an accurate pitch length outcome. The deterministic model also states which contributing factors the release parameter represents and the biomechanical process that it entails. By adopting a deterministic model like this, was to enable the research to clearly define the process of pitch length accuracy and therefore, uncover a story of factors that explain it.

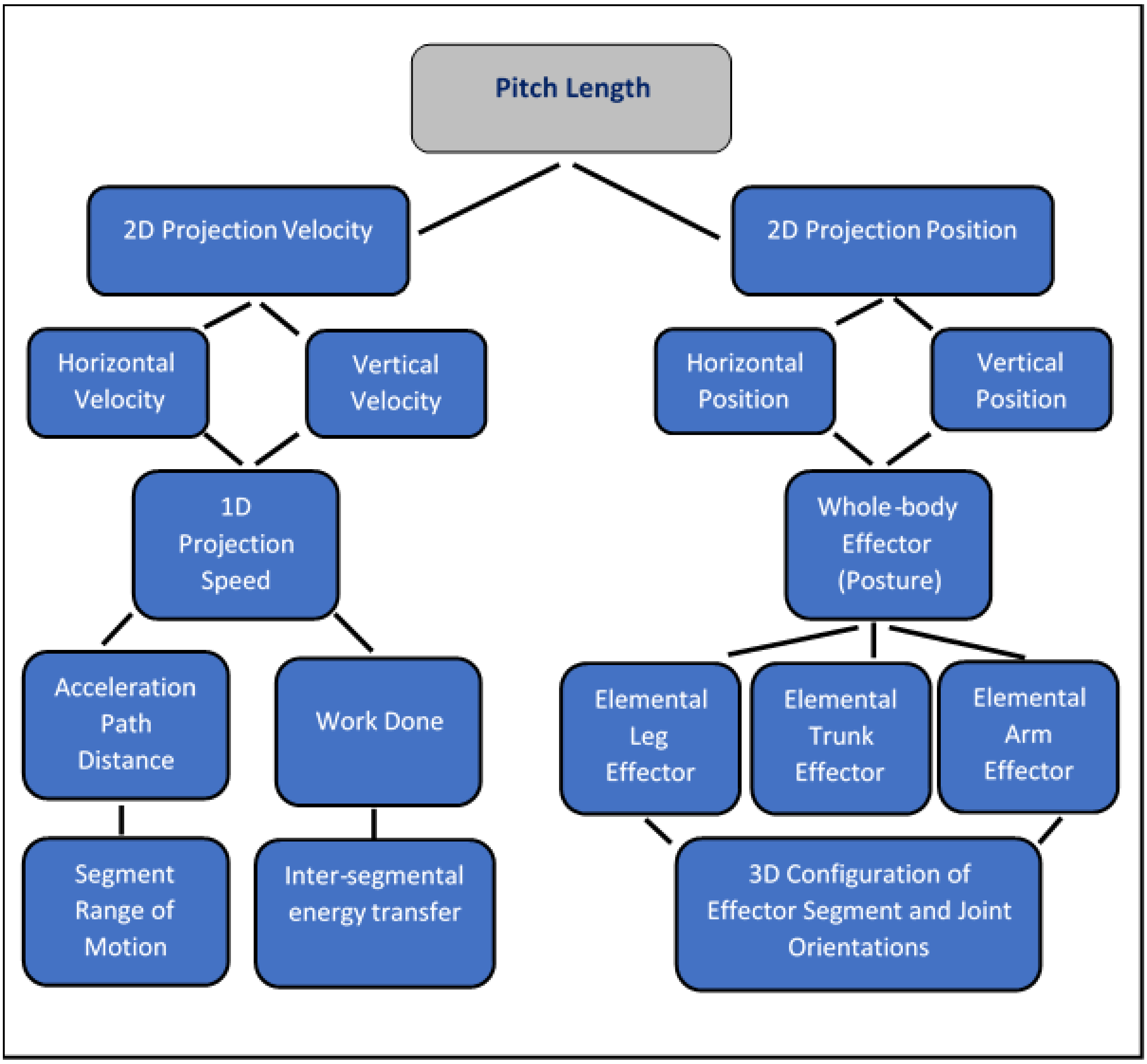

Figure 10.7.3.1: *Deterministic model of contributing ball projection parameters and biomechanical principles that influence cricket fast bowling pitch length.*

10.7.4 Ball release parameters

Two-dimensional BR position and pitch length was determined by the Pitch Coordinate System, defined by the y-axis running wicket-to-wicket and the z-axis pointing vertically. An internal coordinate system was also adopted to obtain intra-participant BR position values by shifting the origin of the coordinate system onto the mid-point of the front foot and projected vertically onto the ground surface. These two coordinate systems worked in conjunction with each other to determine the inter-participant and intra-participant variability of BR parameters.

Table 10.7.4.1: Summary of ball release parameters and how they were derived

Parameter	Description
Ball release position - V_{RP} - H_{RP}	Two-dimensional position (Y, Z) taken at BR event (Harwood et al., 2018). The two-dimensional release position consisted of the vertical release position (i.e., Z or BR height) and horizontal release position (Y or release position from the bowler's stumps) and was recorded in the PCS and SCS for differing purposes. Horizontal release position (H_{RP}) and Vertical Release Position (V_{RP}) results obtained in the PCS were used in pitch length prediction and pitch length accuracy models. This enabled for analysis on pitch length accuracy contribution and co-variability assessment between them and other release parameters. However, release position results obtained in the SCS were used to assess intra-participant variability. The results were then presented as normalised release positions (i.e., vertical release position was expressed as a ratio normalised to the bowler's height and the horizontal position was, likewise, normalised in the same way, by presenting the horizontal ratio of displacement between the ball and MPJC position of the front foot at BR).
Ball release velocity (m/s) - VV_{BR} - HV_{BR}	Ball flight properties were calculated by using simple projectile laws based on constant acceleration, negligible air resistance and computed within the Lab Coordinate System (Worthington et al., 2013a). Ball velocity was based on the first derivative of ball displacement. The metric of ball velocity will be a two-dimensional vector recorded from BR recorded over three frames. The two-dimensional vector will consist of both vertical velocity at ball release (VV_{BR}) and horizontal velocity at ball release (HV_{BR}) and these two variables will be used in pitch length prediction and pitch length accuracy models.
Ball release speed (m/s) BRS	A scalar metric based on the resultant magnitude of the ball two-dimensional velocity vector at BR. (Worthington et al., 2013a)
Ball release angle (α_X, γ_Z) BRθ	Release angle was defined in the sagittal plane. Ball displacement between ten consecutive frames at BR was used to create a two-dimensional vector with angular orientation relative to the PCS. The vertical plane release

	angle was defined by γ_Z (angular displacement about the Z-axis), while the Y-axis remained unchanged (Lindsay & Spratford, 2020).
Observed Pitch Length	A grid system marked by lines every 2 m was placed on the floor of the pitch from the batter's stumps. An observer then manually recorded the length of the pitch with reference to where they saw the ball pitch to the nearest 10 cm on the 2 m marked mat. One observer was positioned to the side of the pitch at the batter's end and recorded every trial of the bowler. The pitch length value obtained from this method was used as a quality control measure with the predicted pitch length.
Predicted Pitch Length	Ball flight properties were calculated by using simple projectile laws based on constant acceleration (over ten frames following BR), negligible air resistance and computed within the Pitch Coordinate System. Pitch length was calculated from the four BR parameter inputs of (i) horizontal velocity (Vz); (ii) vertical velocity (Vy); (iii) horizontal position (Py); and (iv) vertical position (Pz), in a pitch length prediction model, see Equation 1 below. Predicted pitch length was then cross-checked with the manually observed length for each delivery. A more in-depth breakdown of pitch length and method appropriateness can be found in Sections 10.9 and 10.10. Equation 1: BR parameter pitch length prediction model $$Pitch\ Length = 20.12 - \frac{(-Vz - \sqrt{Vz^2 + (2 \times 9.8 \times Pz)})}{-9.8} \times Vy - Py$$
Pitch Length Accuracy	Pitch length accuracy was determined by the standard deviation of each bowler's 18 predicted pitch length deliveries. The mean pitch length was likewise used to determine the individual bowlers goal pitch length.

10.8 ***Effector model***

The biomechanical model was reduced into a three-effector model, where each effector was a three-dimensional position vector spanning a chain of neighbouring body segments. These position effector vectors were simply labelled as the leg effector (Leg), trunk effector (Trunk) and arm effector (Arm). A fourth effector position vector represented the whole-body effector (WB), which was the collective vector sum of the three 'elemental' effectors (see Table 10.8.1 and Figure 10.8.1 for specific details of the anatomical effector endpoints). Each elemental effector measured the length between the origin and the anatomical effector endpoint, with the position vector normalised to subject body height and represented in the laboratory coordinate system (NOTE: positive Y-axis was between middle stump of bowling crease to batting crease, the positive Z-axis vertically upwards, and X-axis was orthogonal according to the right-hand rule). The three-dimensional position of all four effectors was tracked across the acceleration phase of the bowling action. The events that identified this phase are described in section 10.7.2. For the left-handed bowlers, the X-dimension was negated for all effectors to achieve consistent inter-bowler comparisons.

Table 10.8.1: *Definition of effectors and their anatomical endpoint locations.*

Effectors	Effector span and anatomical endpoints
Leg	Three-dimensional position vector that spans the foot, shank, thigh, and pelvis segments of the front leg. The proximal vector endpoint is located at the mid-point of the Metatarsal phalangeal joint (i.e., second metatarsal head) and the distal endpoint is located at the contra-lateral hip joint centre (of the trail leg).
Trunk	Three-dimensional vector that spans the lumbar and thoracic regions of the spinal column, from the lower lumbar to the upper thoracic. The proximal vector endpoint is at the trail (back) leg hip joint centre and the distal endpoint is the ipsilateral shoulder joint centre (i.e., bowling shoulder).
Arm	Three-dimensional vector that spans the upper arm, forearm, and hand segments of the bowling arm. The proximal vector endpoint is located at the shoulder joint centre of the bowling arm and the distal endpoint is located at the 3rd metacarpal phalangeal joint centre of the bowling hand.

Whole-Body	Three-dimensional vector that spans the whole body from the front foot to the bowling hand (i.e., this is the resultant vector of the summed elemental effector vectors described above). The proximal vector endpoint is located at the front foot 2nd metatarsal phalangeal joint centre and the distal endpoint is located at the bowling hand 3rd metacarpal phalangeal joint centre.

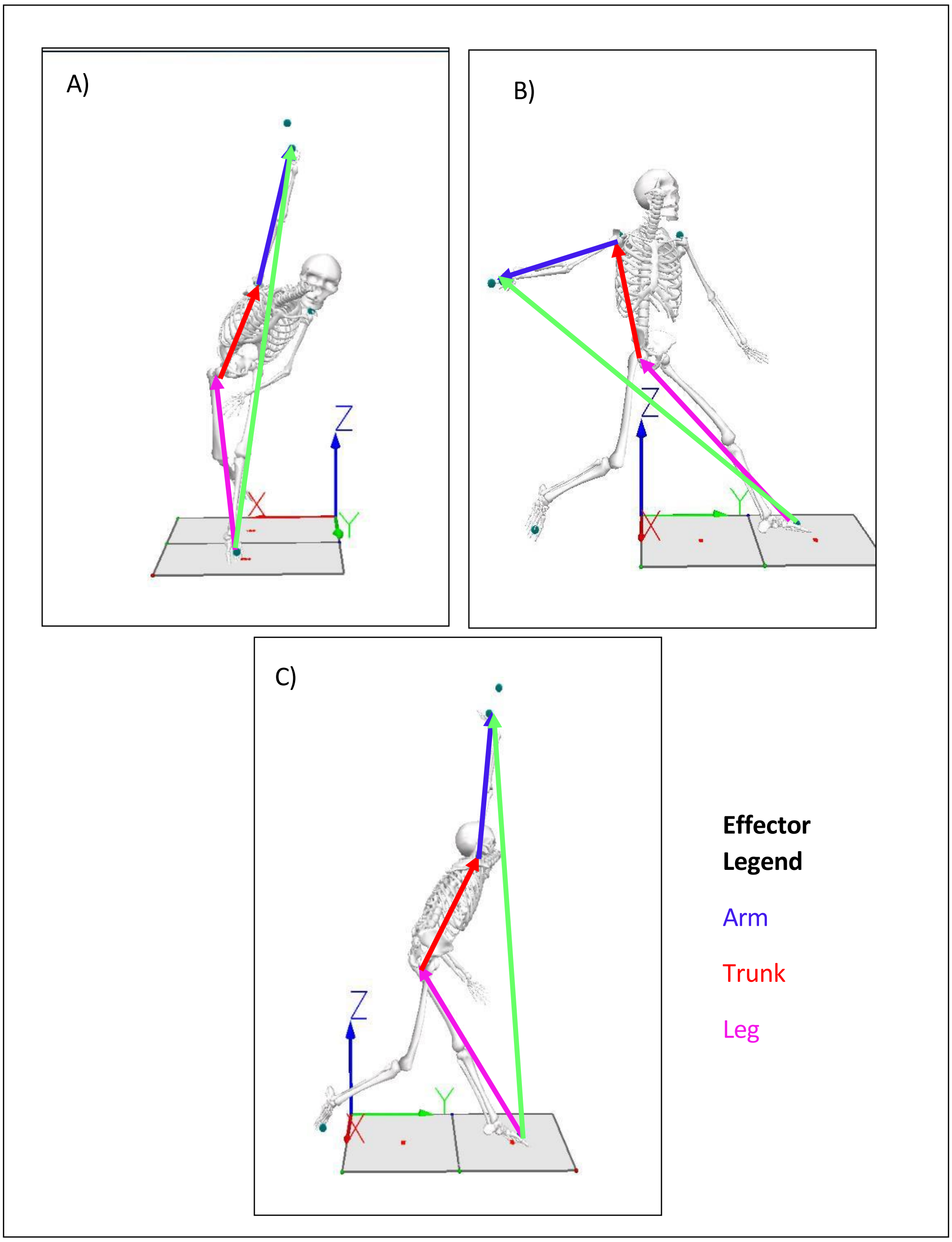

Figure 10.8.1: *Effector model. A) X-dimension, B) Y-dimension, C) Z-dimension*

10.9 Sensitivity analysis of ball release event identification

Several different methods (i.e., ways to determine when the ball has left the bowler's hand) have been used thus far in cricket fast bowling literature to identify this BR event. Traditionally, the identification of BR has been determined from subjective analysis of video film, from the first frame when the ball and fingers separated contact. This observed point in separation has been used previously in cricket-bowling biomechanical studies (Portus et al., 2004).

A more recent method adopted by Worthington et al. (2013a) identified BR by using a time history of the distance between a wrist and ball landmark or marker (Worthington et al., 2013a). The BR event was defined as the first instance that the within-frame ball and wrist distance exceeded 20 mm relative to the previous frame (Worthington et al., 2013a). This method achieves an accurate way to measure release, however it does assume that 20 mm of separation is consistent between all bowlers. This thesis adopted a similar hand-to-ball separation method as Worthington et al. (2013), however it used a different calculation method of the ball to hand separation threshold. This more appropriately reflected the involvement of the fingers with the ball's original position in the hand.

The method adopted to determine BR was recorded at the threshold point where the displacement between two markers exceeded 50 mm. These two markers were created from the marker on the ball and a virtual marker created to represent the palm of the hand, retrospectively created from the marker placed on the 3rd Metacarpal Phalangeal Joint (3MPJ hand marker). To create this virtual ball marker (virtual 3MPJ marker) the distance between the ball marker and the 3MPJ hand marker was separated into fifths. The first fifth, a 20% distance between these two markers, was assumed to approximately reflect the distance between the hand marker's position on the posterior side of the hand in relation to the anterior side, where the back of the ball is thought to rest. This virtual 3MPJ marker was then tracked by the motion of the ball's retro-reflective marker and the 3MPJ hand marker. As the bowler delivered the ball, the ball marker would separate from the virtual 3MPJ marker when an impulse was imparted by the fingers to the ball, from which a cumulative distance evolved. BR was thus assumed to be the first instant whereby a displacement of 50 mm was exceeded between these two markers.

To test the validity of this new method, a sensitivity analysis was performed and the results compared to a previous method. Comparison between both methods found that the BR method adopted in this study recorded the BR frame slightly earlier than did the method adopted by Worthington et al. (2013a) (mean ± standard deviation: -0.51 ± 0.99 frames). This primary evaluation shows that the method adopted in this study is consistent with contemporary methods accepted in cricket fast bowling studies.

To verify the appropriateness of this BR identification method, a sensitivity analysis was conducted to assess its ability to determine BR parameter values and calculated pitch length, via a pitch length prediction model. The adopted sensitivity analysis analysed the determined BR frame, along with the two corresponding frames (±1 frame), recording all BR parameter values at these events. In total, 513 trials were analysed across all different lengths. A smaller standard deviation value for each variable was considered more consistent and, therefore, the better result. From all the BR parameters analysed (HBR, VVBR, and BRθ), the recorded BR position (H_{RP}, V_{RP}) was the most consistent when compared to the frame (Table 10.9.1). This result means that once the ball has been released, the marker position fluctuations due to likely ball rotation can create error. If the method identified that BR event +1 as the release point, it could likely cause inaccurate results.

The most important result of the sensitivity analysis came from the predicted pitch length model, which determined what the expected pitch length of each event would be. As seen in Table 10.9.2, analysis of the frame prior to BR (BR -1) produced an overall mean negative length. This suggests that the pitch lengths of these trials predicted a length beyond the length of the pitch. Such a result indicates that, at this specific event, the ball was likely still in the hand and had not yet been released. Analysis of the frame, post BR (BR +1), produced a more consistent mean pitch length of 4.03 m, however the standard deviation was highly variable (± 6.28 m). This is more than double the expected standard deviation of the observed pitch length (± 3.01 m). In contrast, the identified BR event (mean BR pitch length of 6.47 m) came very close to matching the mean observed pitch length of 6.52 m. The standard deviation was also similar between the two, with the observed pitch length having a standard deviation of ± 3.01 m and the recorded BR event standard deviation of ± 3.45 m across all trials. In summary, the pitch length sensitivity analysis indicates the BR event identified by the new method shows promise to be adopted as an appropriate measure of BR. Thus, it could also be used to appropriately measure any subsequent BR parameter values.

Table 10.9.1: *Ball release parameter sensitivity analysis. Determined release parameter mean and standard deviation per ball release method.*

Ball Release Frame	**Horizontal Velocity ($m \cdot s^{-1}$)**	**Vertical Velocity ($m \cdot s^{-1}$)**	**Ball Release Angle (θ)**	**Vertical Release Position (m)**	**Horizontal Release Position (m)**
Ball Release	**32.01 ± 3.50**	**-4.15 ± 2.25**	**-7.29 ± 3.89**	**2.05 ± 0.22**	**1.04 ± 0.26**
Ball Release +1 Frame	31.48 ± 3.54	-2.88 ± 2.44	-7.82 ± 4.04	2.04 ± 0.22	1.15 ± 0.28
Ball Release -1 Frame	29.73 ± 3.28	0.53 ± 2.44	-7.71 ± 4.07	2.05 ± 0.29	0.92 ± 0.22

Table 10.9.2: *Pitch length sensitivity analysis. Determined mean and standard deviation pitch length per ball release method.*

Ball Release Method	**Mean Pitch Length (m)**	**Pitch Length Standard Deviation (± m)**
Researcher Observed Length	6.52	3.01
Ball Release	**6.47**	**3.45**
Ball Release +1 Frame	4.03	6.28
Ball Release -1 Frame	-3.76	8.53
Researcher Observed Length	6.52	3.01

10.10 Required vertical velocity for mean pitch length

To assess vertical velocity control on pitch length accuracy, an analysis on each participant's ability to match the vertical velocity needed to bowl at their target pitch length was performed. To achieve this analysis, each bowler's target pitch length was defined as their mean performed pitch length. For each trial, their performed vertical velocity was then recorded and removed from the predicted pitch length equation. The equation (see Equation 2) was changed to reflect their goal target length whilst fixing their other three parameters as constants (as per the method of simulated pitch length variance). This equation analyses the change in vertical velocity required by the bowler to satisfy their target pitch length. For example, if a bowler has a required vertical velocity of -3.75 $m \cdot s^{-1}$ to satisfy a target pitch length of 6.50 m, but produces a vertical velocity of -4.0 $m \cdot s^{-1}$, corresponding to a pitch length delivery of 7.0 m, it follows that the performance error in vertical velocity is 0.25 $m \cdot s^{-1}$. This error in required vertical velocity was then described as an average mean, along with the standard deviation of absolute vertical velocity error, and recorded for each bowler. Absolute error was recorded as it could determine the absolute difference between the performed vertical velocity and target vertical velocity. The method is described below.

Target Vertical Velocity: Target Vertical Velocity, $\boldsymbol{V_z}$ is defined by the following:

$$Target\ (Vz) = \frac{-49 \times L^2 + 98 \times L \times Py + 10 \times Pz \times Vy^2 - 49 \times Py^2}{(10 \times Vy \times (L - Py)} \qquad \text{(Equation 2)}$$

Where, ***Vz*** is ball vertical velocity at BR; (ii) ***Vy*** is ball horizontal velocity at BR vertical velocity; (iii) ***Py*** is ball horizontal position at BR; (iv) ***Pz*** is ball vertical position at BR, and (v) ***L*** is the target pitch length.

Mean absolute error and standard deviation of vertical velocity

Standardising the performed vertical velocity as a positive value allowed for the ascertaining of the absolute difference between the target vertical velocity and performed vertical velocity. The mean error and standard deviation were then recorded from all 18 trials.

$$Mean\ Absolute\ Error = |Target\ Vertical\ Velocity - Performed\ Vertical\ Velocity|$$

Standard deviation of vertical velocity error:

The error between target vertical velocity and performed vertical velocity is the same as the above vertical velocity mean absolute error method, except that the performed vertical velocity error was not standardised. An average of the margin of error in the standard deviation was obtained.

10.11 Coordinated covariance test overview

This study explored two major aims related to cooperation of component variables that underscore pitch length control and body position control. To assess whether these hypothesised control parameters (model output) are an outcome of coordinated covariation of underlying variables with an explicit mathematical determination (model inputs), this thesis compared the real variability of the control parameter against its surrogate of simulated variability.

The simulated variability was derived from a mathematical model relating to the control parameter (model output) and the component parameters (model inputs). The real data of the component parameters was independently shuffled in one cycle across the 18 trials to simulate natural variability of that input parameter. The variability of the simulated output was then compared against the real variability of the hypothesised control parameter. If a dependent sample t-test revealed that the simulated variability (after shuffling one input parameter) was significantly larger than the real variability, then the shuffled input parameter was assumed to covary with one or more of the other input parameters. Thus, a significant finding gave support to the claim that the hypothesised control parameter is indeed determined by a collective coordination strategy that involves meaningful cooperation between the model input parameters. This coordination covariance test was applied to two aims: (i) pitch length and BR parameters, and (ii) whole body effector position and the elemental effector units (i.e. leg, trunk and arm). This covariance test has been employed in throwing tasks (Kudo et al., 2000; Nasu et al., 2014; Kusafuka et al. 2022), as well as sport movements such as in springboard diving (Sayyah et al., 2018). The details of the coordination covariance test explicit to each aim is described in the Sections 10.12.1 and 10.12.2 below.

10.11.1 Coordinated covariation test of pitch length and ball release parameters

To calculate the pitch length from the shuffled parameters, one of the BR parameters (horizontal velocity (Vz); (ii) vertical velocity (Vy); (iii) horizontal position (Py); and (iv) vertical position (Pz)) (or horizontal and vertical release velocity parameters) were shuffled 18 times individually through this equation for each individual trial. This equation (Equation 3) was adapted from the pitch length prediction equation (Equation 1) to facilitate the simulated shuffle. The new obtained pitch lengths (18 new lengths) for each trail were then averaged for their mean participant value. The overall standard deviation from those mean pitch length values were then taken and assessed against the performed pitch length variance by Index of Cooperation.

$$New\ Pitch\ Length = 19.52 - Py - \frac{Vy *\ \sqrt{Vz^2 + 19.6 * Pz - Vz}}{-9.8} \qquad \text{Equation 3}$$

Kusafuka et al. (2022) used a simulation model to assess parameter covariance for pitch length control in baseball pitching by shuffling a set of 1000 surrogate input values. In contrast, this study simply cyclically shuffled real data from a small set of 18 real trials. An 18 by 18 cyclical shuffle meant that for each trial where there were four independent variables (i.e., VV_{BR}, HV_{BR}, V_{RP}, and H_{RP}) one of these variables was shuffled independently 18 times for each individual delivery, and thus repeated for all 18 trials. Therefore, 324 random sets were created and the average value and variability of these new simulated pitch locations was compared to the actual performed pitch length variability of each bowler; so as to evaluate release parameter coordinated covariation (see Figure 10.11.1.1).

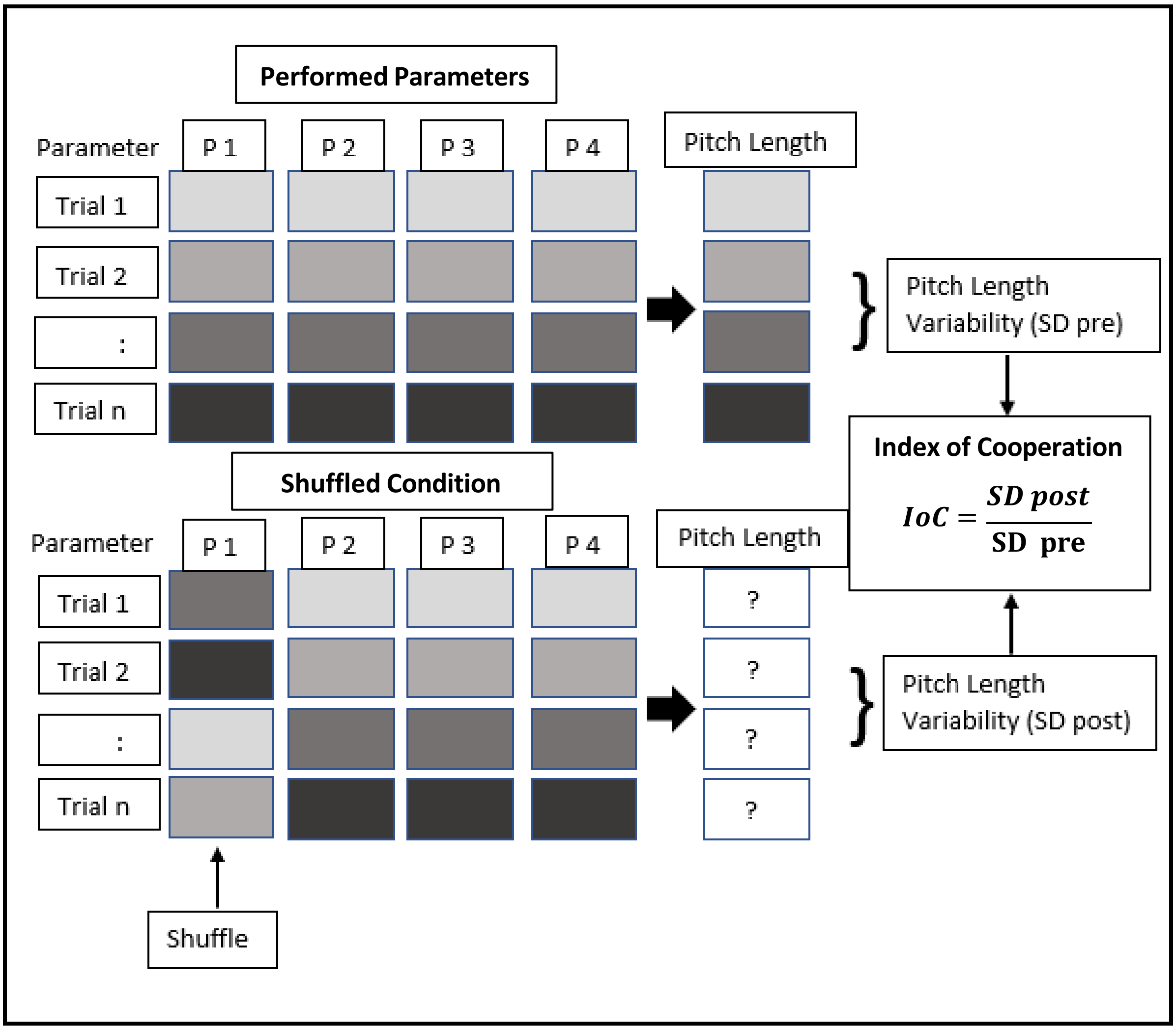

__Figure 10.11.1.1__: Schematic of the ball release parameter coordinated covariance test. Simulated pitch length variability, whereby each ball release parameter (shuffled condition) was cyclically shuffled 18 times independently of other parameters was shown. How much the shuffled pitch length variability differed from the performed pitch length variability was examined through the Index of Cooperation (IoC). Variability of pitch length location in the actual performed condition was set to one.

Coordinated covariation was then defined as a ratio (i.e., Index of Cooperation) between simulated shuffle results and performed pitch length variability. This ratio was taken from dividing the pitch length standard deviation post-shuffle by the performed pitch length standard deviation pre-shuffle. An IoC value of one was defined as the variance of the performed pitch location. By defining the performed pitch location as one, it can be interpreted that with an IoC result of greater than one, it is more likely that coordinated covariation between parameters was occurring to reduce variability of the pitch length location. This is illustrated in Figure 10.11.1.2 whereby, if the fast bowlers' release parameters are coordinated with each other, the variability should increase after the coordination of performed parameters is broken. Otherwise, if the coordination remains relatively unchanged, then the release parameters do not cooperate between each other and, therefore, pitch length control is not likely to be maintained through coordinated covariation.

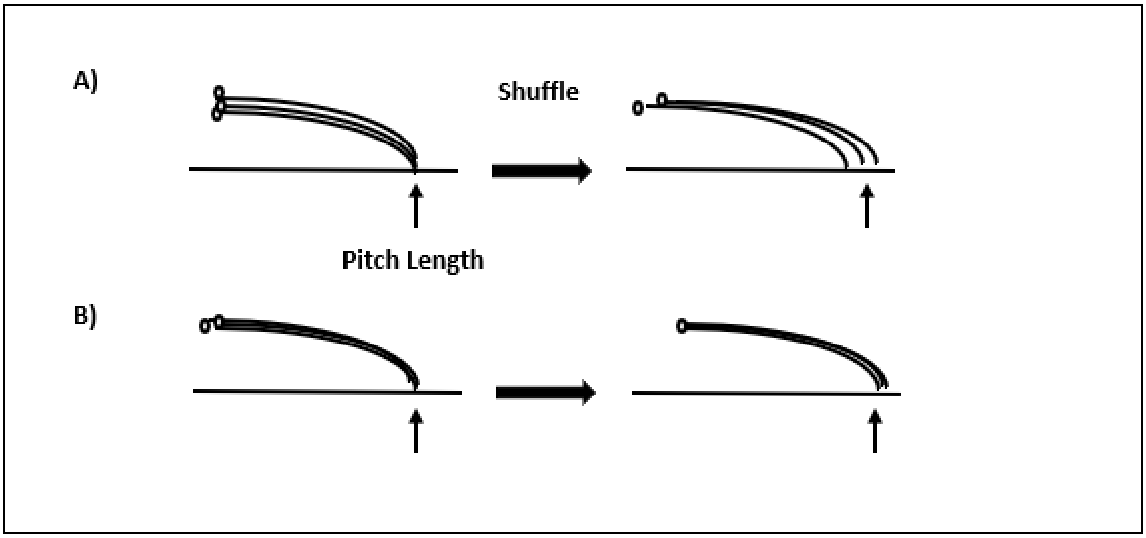

__Figure 10.11.1.2:__ Hypothetical effect on ball flight trajectories following an independent and cyclical reshuffle of one ball release parameter. A) Example of coordinated covariance of the ball release parameters and relationship with pitch length consistency is changed after simulated variation. B) Trajectories when this relationship is unchanged after simulated variance (cyclically reshuffling input parameters).

10.11.2 Coordinated covariance test of body posture and elemental effectors

The simple vector loop model was used to assess whether coordinated covariation of elemental effector parameters was underlying the whole-body effector position, where the whole-body effector is the resultant vector of the summed elemental vectors (i.e., effectors defining the Leg, Trunk and Arm). A simulated whole-body effector variability (S_WBEV) was compared to the real variability of the whole-body effector (WBEV). Inter-effector cooperation shuffling was conducted at three key events of the acceleration phase (FFC, MID and BR). This cyclical shuffling consisted of 18 performed displacement effector results (Figure 10.11.2.1). In total, performing an 18 by 18 cyclical shuffle meant that for each trial, there were three independent variables (i.e., elemental effectors: S_WBEV_{arm}, S_WBEV_{trunk} and S_WBEV_{leg}) to be shuffled separately 18 times for each individual delivery and, thus, repeated for all 18 trials per bowler. Therefore, 324 random simulated sets were created, and the standard deviation of these new S_WBEV was recorded. The mean standard deviation (i.e., variability) of the S_WBEV of each individual bowler indicated the variability arising from the elemental effectors. These standard deviations were then mean averaged as a group to represent the S_WBEV of the bowling cohort. This simulated whole-body effector variability (S_WBEV) was then compared to the actual performed mean whole-body effector variability (WBEV) of the group.

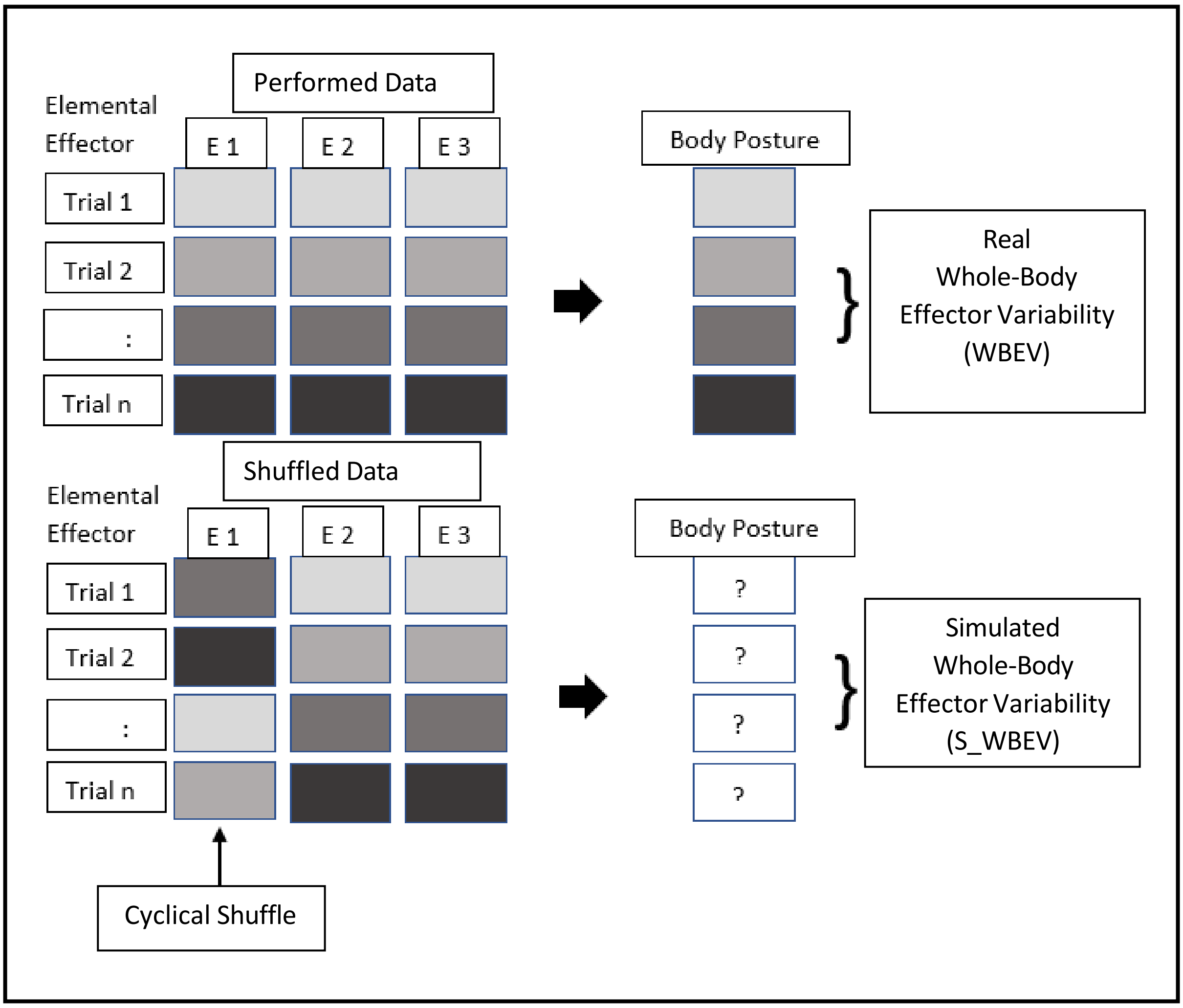

Figure 10.11.2.1: *Effector coordinated covariance test. Simulated whole-body effector variability, whereby elemental effector parameter (shuffled condition) was cyclically shuffled 18 times independently of other parameters as shown. Different shaded boxes under E1 indicate how each trial was cyclically shuffled through the model. How much the S_WBEV differed from the performed pitch length variability WBEV was then determined via a paired-samples t-test.*

10.12 Statistics and data analysis

Vertical velocity variability: This was determined by taking the mean average of the standard deviation of the 12 bowlers' vertical velocity. Vertical velocity standard deviation was then used in the BR parameter regression analysis to determine the effect of vertical velocity variability on pitch length variability and represented the amount of variability in that BR parameter.

Horizontal velocity variability: This was determined by taking the mean average of the standard deviation of the 12 bowlers' horizontal velocity. Horizontal velocity standard deviation was then used in the BR parameter regression analysis to determine the effect of horizontal velocity variability on pitch length variability and represented the amount of horizontal variability amongst the bowling cohort.

Vertical position variability: Mean and standard deviation of height of BR was recorded at the BR event in the PCS. Bowler parameter values were used in the pitch length prediction model, whilst the standard deviation of the 12 bowlers' 18 trials were used in the BR parameter regression analysis to determine the effect of vertical position variability on pitch length variability.

Horizontal position variability: Mean and standard deviation of horizontal release position of BR was recorded at the BR event in PCS. Bowler parameter values were used in the pitch length prediction model, whilst the standard deviation of the bowlers' 18 trials were used in the BR parameter regression analysis to determine the effect of horizontal position variability on pitch length variability.

Pitch length variability: Pitch length was calculated from the four BR parameter inputs of (i) horizontal velocity (Vz); (ii) vertical velocity (Vy); (iii) horizontal position (Py); and (iv) vertical position (Pz), in a pitch length prediction model, see below Equation 1. Mean pitch length of the bowlers' 18 good length trials was used to represent the target length. Pitch length standard deviation of the bowlers' 18 trials was used to present the bowlers' pitch length control (i.e., accuracy).

$$Pitch\ Length = 20.12 - \frac{(-Vz - \sqrt{Vz^2 + (2 \times 9.8 \times Pz)})}{-9.8} \times Vy - Py \qquad \text{(Equation 1)}$$

Whole-body effector variability: Standard deviation of the whole-body effector was recorded from the bowlers' 18 trials. The standard deviation then represented the variability of that effector vector system across the bowling action and at specific events. The performed whole-body effector variability (WBEV) was then used to assess for coordinated covariance of the effector system against the simulated whole-body effector variability (S_WBEV).

10.12.1 Statistical aims

Aim 1: Aim 1 addressed two sub-questions. The first question was to determine what BR parameter (or combinations thereof) is/are most responsible for controlling pitch length variability. The second question asked whether the four release parameters interacted with a coordinated covariance in a group of emerging fast bowlers.

These questions were investigated by analysing the dependent variables of pitch length, BR position and BR velocity. Box plots of BR parameters and pitch length for the bowling group were used to describe normal distribution of results amongst the bowling cohort.

A multiple linear regression analysis was employed to investigate the first question: what combination of BR parameters explains most of the variability in the pitch length? The pitch length variability was the dependent variable in the regression model, whilst the four BR parameters (horizontal velocity, vertical velocity, horizontal position, and vertical position) were the independent variables. The percentage of variance in the dependent variable explained by the independent variables was determined by the R-Squared value. p-value of $<.05$ was used to determine significance of the regression model and independent variables in describing variance of the dependent variable.

A coordination covariance test was used to investigate the second question: are BR parameters showing evidence of cooperation to achieve a consistent pitch length?

The Index of Cooperation was determined by the ratio between SD-post and SD-pre of the pitch length, where the SD-pre is the real variability, while the independent variable (SD-post) was determined by calculating the pitch length standard deviation of the simulated shuffle pitch lengths.

Aim 2: Aim 2 investigated the mean profiles of the four effector units, and the nature of their variability across the acceleration phase.

The waveform mean and standard deviation of the four position effectors (Leg, Arm, Trunk and Whole-body) were compared using time history graphs. Each bowler's 18 trials were used to create a mean effector waveform in all three dimensions using time slices at 10 equally spaced intervals from their time-normalised acceleration phase. The same time-slicing approach was used for each bowler's 18 trials to create a variance waveform profile across the acceleration phase. These two profiles were then averaged across the group and used to represent the overall variability of the four effector units within each spatial dimension (X, Y, Z).

Aim 3: Aim 3 investigated whether the elemental effectors could explain the vertical velocity variability.

A multiple stepwise linear regression analysis was used to test this question. The dependent variables were the three-dimensional effector positions (mean and standard deviation metrics) taken at the three events of the acceleration phase (FFC, MID, BR). The regression model independent variable was the bowler's vertical velocity variability metric at BR. A stepwise method was used because it could find the optimal combination of explanatory variables (i.e., effector inputs) by reducing the number of explanatory variables from the most complex model. All parameters with a significance p-value larger than .05 ($p > .05$) were reduced from the model. The percentage of variance in vertical velocity variability explained by the independent (predictor) variables was determined by the R-Squared value. The model was considered significant if the amount of variance explained was significant at p-value less than .05.

Aim 4: Aim 4 investigated evidence of coordinated covariance between the elemental effectors.

A whole-body effector model was represented by the vector sum expression of the elemental effector vectors in their respective dimensions (X, Y, Z). To determine the existence of coordinated covariance a paired-sample t-test was performed to assess the statistical difference between the simulated variance of the whole-body effector (i.e., S_WBEV) and the true variance (WBEV). The method was applied for all three effectors and all three dimensions, and at the three key events of the acceleration phase (i.e., FFC, MID and BR). If inter-effector cooperation did exist, it was expected that the WBEV would be significantly lower than the S_WBEV, thus indicating that effector position variations are not simply random deviations but serve some functional purpose to reduce unwanted variations in the whole-body effector position.

10.13 Statistic software

All BR parameter, effector vector statistics and regression analyses were performed through IBM SPSS Statistics v. 27 (IBM, Armonk, NY, USA). Matlab v.2021a (The MathWorks Inc., Natick, MA, USA) was adopted to perform the coordinated covariance test and simulate model variance using a cyclical shuffle command from Matlab. All graphs and figures were constructed within GraphPad (GraphPad Software, San Diego, CA, USA) and Inspect3D (C-Motion Inc., USA).

11.0 Results

11.1 <u>Release parameter cooperation and pitch length variability</u>

<u>Aim 1: What is the nature of cooperation among the four projection parameters of horizontal and vertical release velocity and two-dimensional release position? Which parameter, or combination of parameters, is most responsible for describing pitch length variability?</u>

In this study, 552 balls of varying lengths were bowled by the cohort, of which 288 were of good length suitable for analysis. All but two bowlers bowled a full quota of eight overs. However, all bowled 24 balls which were of a good length. The first 18 trials of the bowlers were analysed, from which two outliers were removed from the data due to Vicon analysis error and replaced by the data from the following good length delivery (i.e., 19^{th} trial).

The twelve bowlers produced a mean and standard deviation ball pitch length of 6.12 ± 1.89 m (Table 11.1.1) and median pitch length variability of 1.86 m (Figure 11.1.1). Of the BR parameters, vertical velocity standard deviation was found to be more variable than the horizontal velocities standard deviation, whilst vertical position (V_{RP}) too was less variable than the horizontal position (H_{RP}) at BR (Table 11.1.1). The variability relationship between vertical (VV_{BR}) and horizontal velocity (HV_{BR}) standard deviations was similar amongst the bowling group, with only bowlers 3 and 11 producing greater standard deviations in their HV_{BR} compared to their VV_{BR} (Table 11.1.1). The least variable VV_{BR} (0.86) was observed in bowler 1, whom also had the lease variable pitch length (1.52) A difference in standard deviation of 0.74 m was observed between the most and least variable pitch lengths.

__Table 11.1.1:__ Individual bowler's ball release parameter and pitch length mean and standard deviation values.

Bowler	Vertical Velocity ($m \cdot s^{-1}$)	Horizontal Velocity ($m \cdot s^{-1}$)	Vertical Position (m)	Horizontal Position (m)	Pitch Length (m)
1	-3.70 ± 0.86	33.20 ± 0.64	1.81 ± 0.15	1.90 ± 0.02	6.54 ± 1.52
2	-4.52 ± 1.02	34.70 ± 0.95	1.59 ± 0.17	2.12 ± 0.025	6.53 ± 1.69
3	-3.55 ± 0.91	33.67 ± 1.05	1.19 ± 0.12	2.02 ± 0.03	6.12 ± 1.69
4	-4.60 ± 1.23	29.77 ± 0.89	1.61 ± 0.17	2.11 ± 0.03	8.29 ± 1.72
5	-3.56 ± 1.04	32.34 ± 0.34	1.54 ± 0.14	2.08 ± 0.02	6.03 ± 1.72
6	-4.52 ± 1.02	33.45 ± 0.50	1.59 ± 0.17	2.04 ± 0.01	4.19 ± 1.85
7	-3.31 ± 1.17	30.57 ± 0.71	1.96 ± 0.12	1.92 ± 0.02	6.54 ± 1.86
8	-3.67 ± 1.07	33.44 ± 0.65	1.68 ± 0.21	2.05 ± 0.02	5.78 ± 2.00
9	-3.80 ± 1.21	31.69 ± 0.82	1.61 ± 0.11	2.09 ± 0.02	6.50 ± 2.02
10	-4.24 ± 1.30	34.38 ± 1.11	1.81 ± 0.14	2.09 ± 0.025	6.02 ± 2.13
11	-3.55 ± 0.91	30.23 ± 1.30	1.19 ± 0.12	2.19 ± 0.02	4.86 ± 2.24
12	-3.56 ± 1.04	30.74 ± 0.71	1.54 ± 0.14	2.19 ± 0.02	6.09 ± 2.28
Group	-3.69 ± 1.11	32.35 ± 0.81	1.65 ± 0.14	2.07 ± 0.02	6.12 ± 1.89

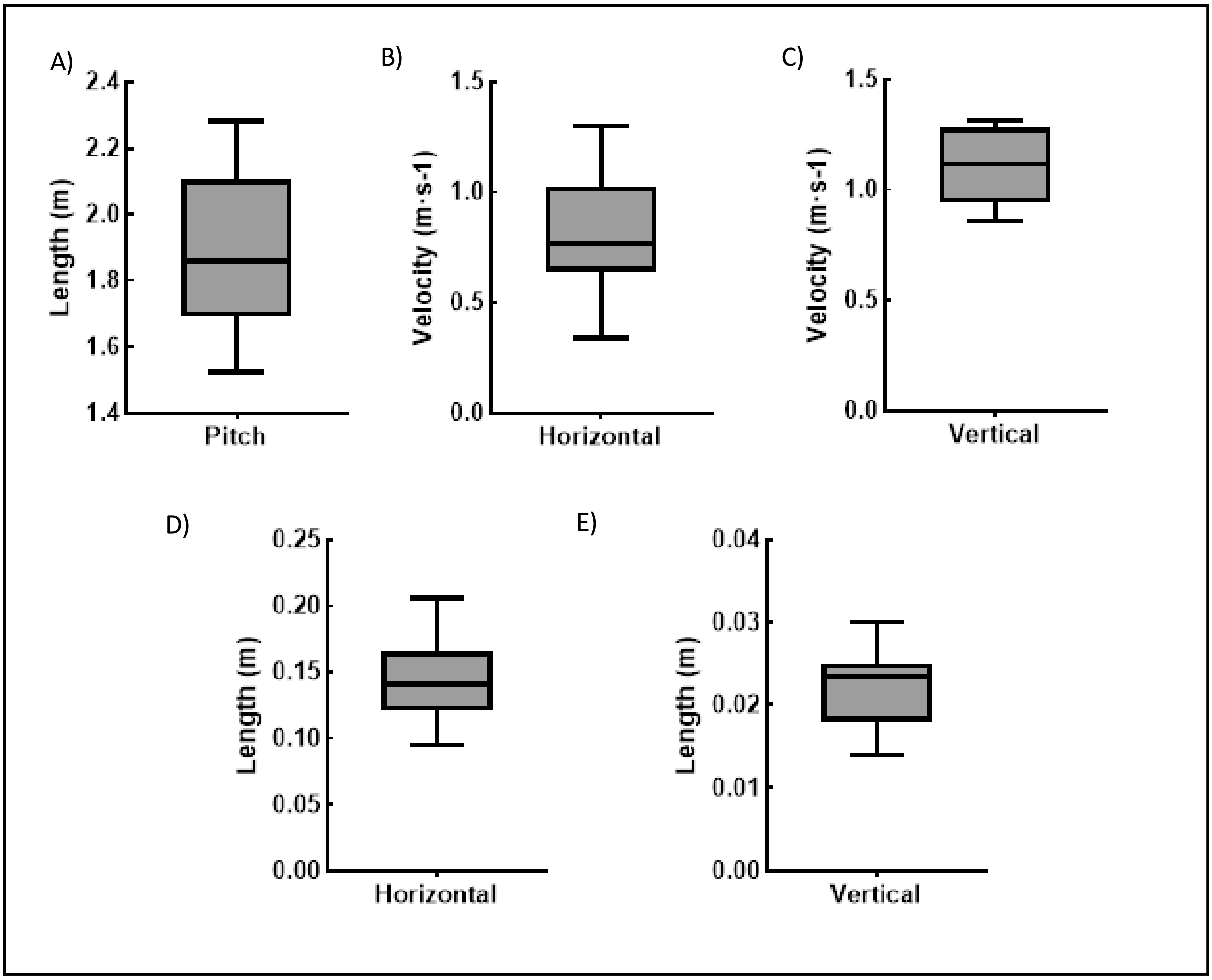

***Figure 11.1.1**: Box and whisker plots showing the group median and quartile distribution of release parameter standard deviations: a) pitch length standard deviation b) horizontal velocity standard deviation c) vertical velocity standard deviation d) horizontal position standard deviation e) vertical position standard deviation.*

A pitch length sensitivity analysis was conducted to assess which BR parameter was likely to cause the biggest influence on pitch length. One standard deviation value from the mean was tested and found VV_{BR} would cause the biggest change in predicted pitch length. A change of one standard deviation value produced a pitch length of 2.54 m (Table 11.1.2).

Table 11.1.2: Pitch length sensitivity analysis. Change in one standard deviation of mean release parameter values effect on predicted pitch length. Bold data represents the change in one standard deviation of that release parameter.

	Pitch Length (m)	Change in Pitch Length (m)	Horizontal Position (m)	Vertical Position (m)	Horizontal Velocity ($m \cdot s^{-1}$)	Vertical Velocity ($m \cdot s^{-1}$)
Performed	6.19		1.65	2.07	32.4	-3.7
	6.04	0.15	**1.8**	2.07	32.4	-3.7
	6.19	0.00	1.65	**2.03**	32.4	-3.7
	6.89	-0.70	1.65	2.07	**30.5**	-3.7
	2.54	3.65	1.65	2.07	32.4	**-4.8**

A multi-linear regression was used to test if the four release parameters predict pitch length variability. The fitted regression model was (Pitch Length) $P = .731 + .270\ HV_{BR} + 1.313\ VV_{BR} + .618\ H_{RP} + -27.594\ V_{RP}$). The overall regression was statistically significant ($R^2 = .789$, *95% CI = -0.2677 to 1.743*, $F\ (4, 7) = 6.55$, $p = .016$). It was found that only VV_{BR} variability (standard deviation) was a significant predictor of pitch length variability ($\beta = 1.313$, $R^2 = .903$, t-$(7) = 4.437$, $p = 0.003$). All other variables were not significant predictors of pitch length variability and carried a lower weighting (HV_{BR} variability $p = .270$, H_{RP} variability $p = .710$, V_{RP} variability $p = .057$).

An equation that modelled the mechanical relationship between the release parameters and pitch length was used to compare the different contributions of independently varying (cyclic shuffling) a release parameter score (from the bowler's observed set of scores) on the modelled pitch length variability (see Methods Section 10.12.1). The assumption is that when pitch length variability increases remarkably following a cyclic shuffle of an input parameter, then that particular parameter is deemed an important contributor of pitch accuracy. Table 11.1.3 shows that pitch length variability (accuracy) was not more (or less) variable than a random variation of the model input parameters (Table 11.1.3). Results from the Index of Cooperation revealed the co-variability of each parameter on pitch length variability (Table11.1.3). The IoC showed no distinction in pitch length variability after each parameter was shuffled. Table 11.1.4 presents details at the individual level, where each bowler's Index of Cooperation for each release parameter shuffle reveals no remarkable change in co-variability and demonstrates a relative uniformity amongst the bowling group. Neither more nor less accurate bowlers had a greater overall control of their pitch length variability from release parameter control.

Table 11.1.3: *Group pitch length standard deviation and Index of Cooperation values for cyclically shuffled parameters.*

Ball Release Parameter	**Pitch Length SD (m)**	**Index of Cooperation (IoC)**
Recorded Parameters	1.89	1.00
Vertical Velocity	1.90	1.01
Horizontal Velocity	1.91	1.01
Vertical Position	1.88	0.99
Horizontal Position	1.90	1.01
Vertical/Horizontal Velocity	1.88	1.00

Table 11.1.4: *Bowler's pitch length standard deviation and Index of Cooperation values for cyclically shuffled release parameters. The bold font is included to indicate when a bowler's recorded pitch length variability was less than the variability from the cyclic shuffle of the inputs.*

Bowler	**Pitch Length (m)**		**Vertical Velocity ($m \cdot s^{-1}$)**		**Horizontal Velocity ($m \cdot s^{-1}$)**		**Vertical Position (m)**		**Horizontal Position (m)**		**Vertical/ Horizontal Velocity ($m \cdot s^{-1}$)**	
	SD	IoC	SD	IoC	SD	IoC	SD	IoC	SD	IoC	SD	IoC
1	1.52	1.00	1.40	0.92	1.43	0.94	**1.55**	**1.01**	1.49	0.98	1.51	0.99
2	1.69	1.00	1.64	0.97	1.73	**1.03**	1.64	0.97	1.65	0.98	1.60	0.94
3	1.69	1.00	1.65	0.98	1.61	0.96	**1.71**	**1.01**	**1.74**	**1.03**	**1.77**	**1.05**
4	1.72	1.00	1.60	0.93	1.65	0.96	1.68	0.98	1.68	0.98	1.63	0.95
5	1.72	1.00	**1.81**	**1.05**	**1.75**	**1.02**	1.71	1.00	**1.78**	**1.04**	**1.78**	**1.04**
6	1.85	1.00	**1.91**	**1.03**	1.84	0.99	1.85	1.00	**1.92**	**1.04**	**1.92**	**1.04**
7	1.86	1.00	**1.98**	**1.06**	**1.98**	**1.06**	1.84	0.99	**1.89**	**1.01**	1.86	1.00
8	2.00	1.00	1.88	0.94	1.88	0.94	1.99	0.99	**2.01**	**1.00**	**2.01**	**1.00**
9	2.02	1.00	1.97	0.97	2.01	1.00	2.00	0.99	1.99	0.99	1.97	0.97
10	2.13	1.00	2.06	0.97	2.07	0.97	**2.16**	**1.01**	2.10	0.99	2.13	1.00
11	2.24	1.00	**2.56**	**1.14**	**2.61**	**1.17**	2.20	0.98	2.24	1.00	2.14	0.95
12	2.28	1.00	**2.35**	**1.03**	**2.34**	**1.03**	2.25	0.98	**2.33**	**1.02**	**2.29**	**1.00**

The bowling group was expected to meet a performance target (a mean pitch length of 6.12 m), which corresponds to a mean vertical velocity of -3.85 $m \cdot s^{-1}$. Table 11.1.5 shows the variability (standard deviation) of the error between the performed vertical velocity, where the group average error was ±1.13 $m \cdot s^{-1}$ and a group mean absolute error of 0.93 $m \cdot s^{-1}$.

Table 11.1.5: *Group and individual bowlers' mean target vertical velocity values (velocity required to meet the performance target pitch length) and mean absolute error and recorded standard deviation of performed vertical velocity to target vertical velocity.*

Bowler	**Target Pitch Length (m)**	**Target Vertical Velocity ($m{\cdot}s^{-1}$)**	**Mean Absolute Error**	**Error SD**
1	6.54	-4.00	0.86	0.95
2	6.53	-4.83	0.93	1.10
3	6.12	-3.43	0.66	0.91
4	8.29	-4.94	1.13	1.34
5	6.03	-3.47	0.81	0.99
6	4.19	-2.91	0.73	0.89
7	6.54	-3.55	0.87	1.11
8	5.78	-3.90	0.94	1.15
9	6.50	-4.04	1.04	1.25
10	6.02	-4.46	1.10	1.37
11	4.86	-2.93	0.98	1.24
12	6.09	-3.66	1.04	1.31
Group	6.12	-3.85	0.93	1.13

11.2 Nature of effector variability

Aim 2 Results: What is the nature (time, dimension) of effector displacement and variability in the effector systems?

11.2.1 Effector displacement across the acceleration phase

Figures 11.2.1.1, 11.2.1.2 and 11.2.1.3 present the mean effector displacement waveforms of the whole-body effector across the acceleration phase (i.e., FFC to BR). From these waveforms all effector displacement variability and values are obtained at even time slices and key events during this phase.

X-dimension effector displacement is shown by Figure 11.2.1.1. Effector waveforms in the X-dimension show numerous bowling techniques employed by the bowling cohort to deliver the ball from FFC to BR. End-point position of the bowling hand for the bowlers varied between a more lateral (positive) or medial (negative) position to the origin of the whole-body effector (MPJC). A medial position indicates the bowlers release point is more medially flexed over the MPJC. The group mean waveform in the X-dimension is presented this way and the most medial position of the effector being recorded just after the mid-point of the acceleration phase, or during the bowling arms circumduction.

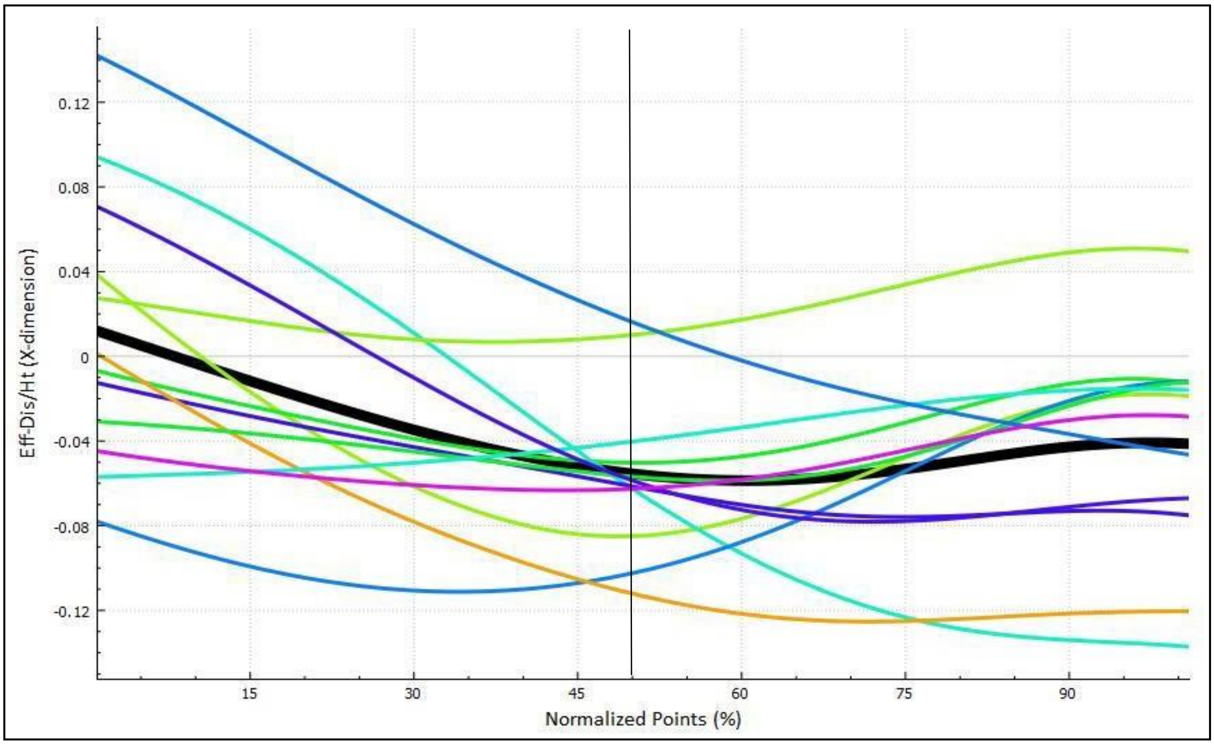

Figure 11.2.1.1: Signal graph of the whole-body effector displacement waveforms in the X-dimension across the acceleration phase. Individual bowler's mean waveforms are represented by each colour with the group mean waveform represented by the bold black line.

Figure 11.2.1.2 presents the whole-body effector displacement in the Y-dimension. The waveform shows a similar displacement path between the bowling cohort, with the hand (effector endpoint) remaining in a posterior position to the MPJC (effector origin) until BR for all but five bowlers. The mean group position of the hand at BR was slightly posterior to the MPJC.

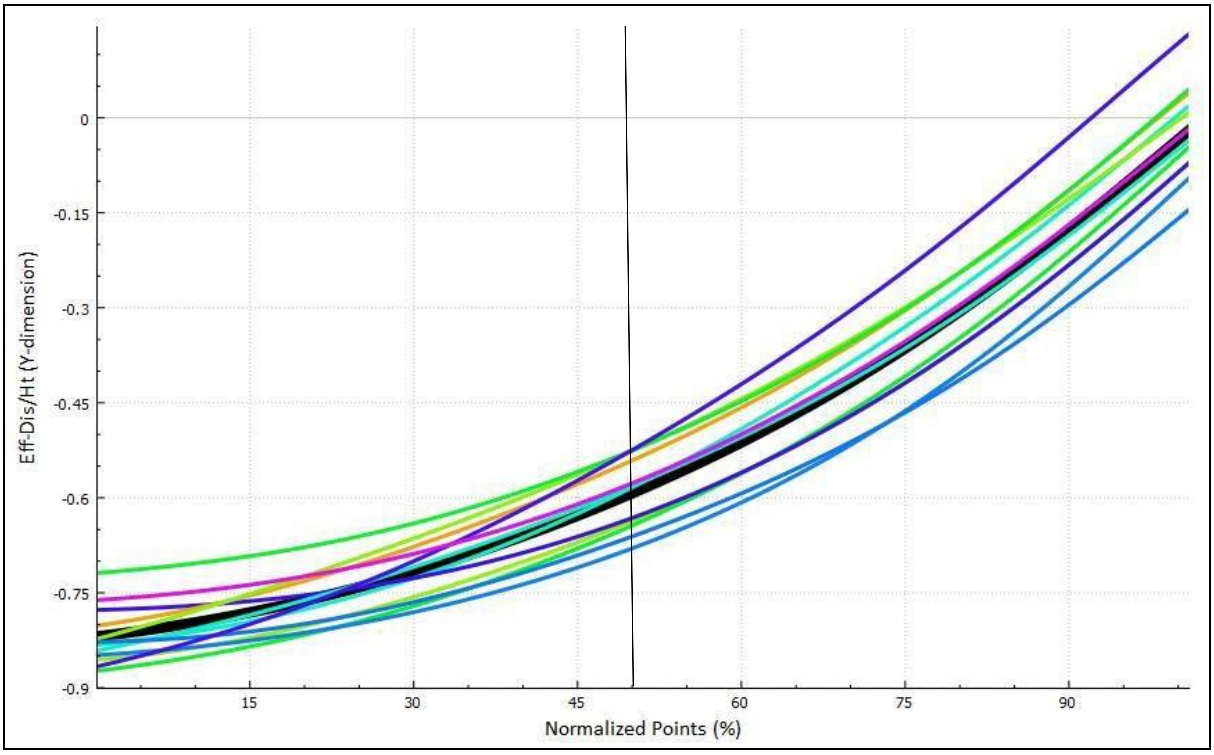

Figure 11.2.1.2: Signal graph of effector displacement waveforms in the Y-dimension across the acceleration phase. Individual bowler's waveform means are represented by each colour with the group mean represented by the bold black line.

The Z-dimension waveform is described by Figure 11.2.1.3. Height of the hand in relation to the MPJC effector origin showed the bowlers employed different mean displacement heights of the hand throughout their action. Some bowlers remained more upright and bowled the ball at release above their standing height. However, two bowlers released the ball at a point below their standing height. These waveforms indicate differences in bowling technique adopted amongst the cohort. The group mean displacement value at BR was 1.01% of standing height.

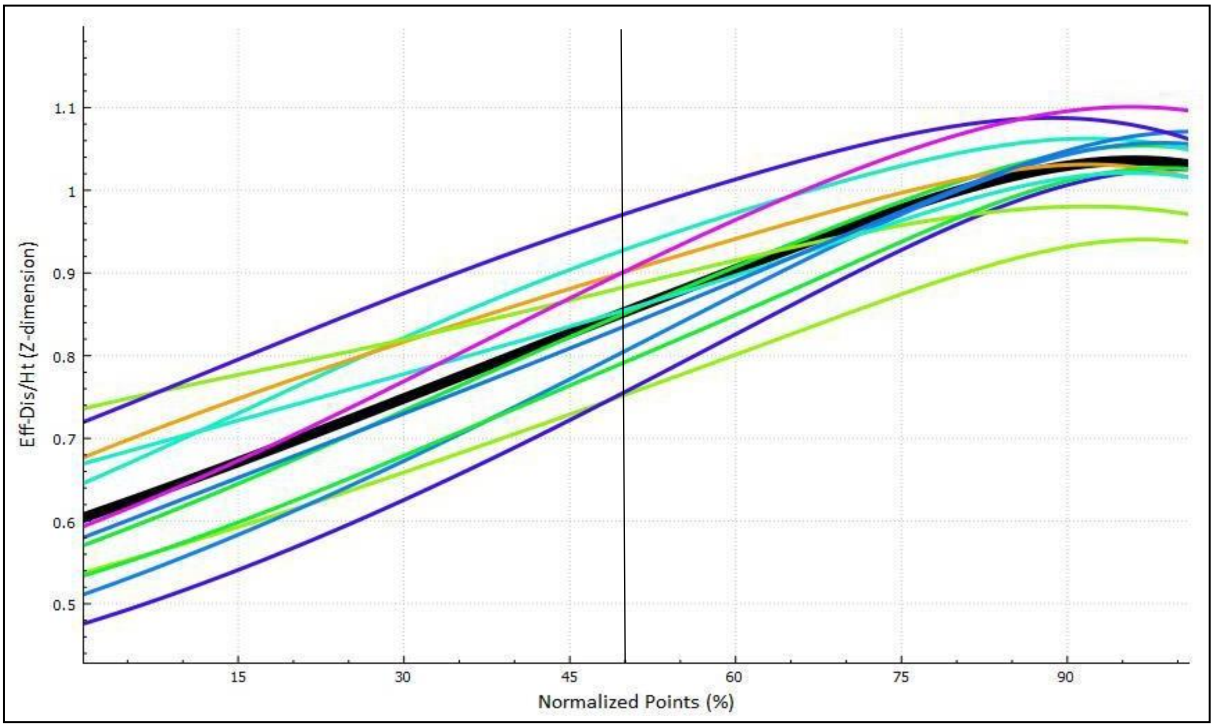

***Figure 11.2.1.3**: Signal graph of effector displacement waveforms in the Z-dimension across the acceleration phase. Individual bowler's waveform means are represented by each colour with the group mean represented by the bold black line.*

Figure 11.2.1.4 presents the group mean minimum and maximum effector displacement. This indicates the average range of motion (i.e., displacement) each effector travels during the acceleration phase. It is evident that the majority of whole-body effector displacement comes from the arm effector, especially in the Y and Z-dimensions. In the X-dimension the bowler's mean and minimum leg effector displacement remains low, only increasing by 0.03%, from a minimum of 0.03 to a maximum of 0.06. The largest displacement result came from the whole-body effector in the Y-dimension. Bowlers' mean maximum was -0.82% of body height and minimum was -0.03 %.

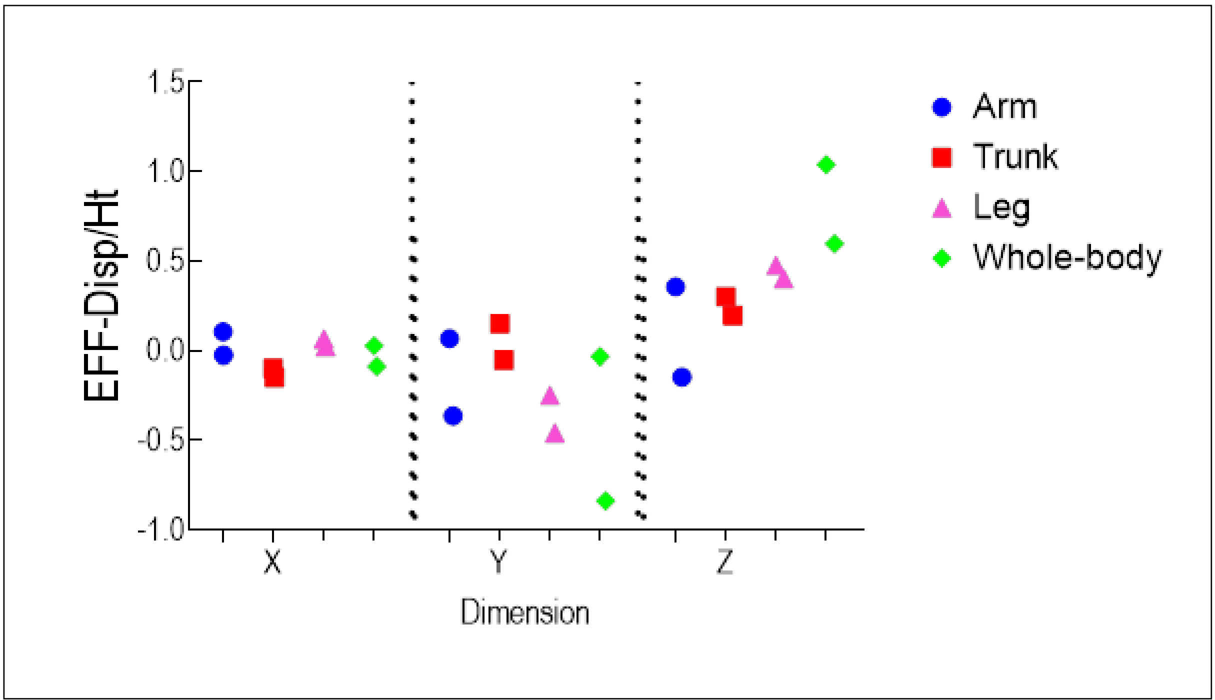

Figure 11.2.1.4: *Group mean minimum and maximum effector displacement during the acceleration phase.*

11.2.2 Effector position and variability at key events

This section of the results will present effector position and effector variability at key events of the time normalised acceleration phase. Both elemental and whole-body effector variability will be described.

Figure 11.2.2.1 shows the group mean and standard deviation of effector position at each event in the X-dimension. Mean position of the arm and leg remained in a positive direction at all three events, whilst the trunk and the whole-body were positioned negatively. This indicates the trunk influences the whole-body effector position greatly in this dimension. Positive and negative values are good indicators of bowling technique used. A positive value in the X-dimension of the leg, for instance, indicates the hip joint centre is outside of the alignment of the origin of the MPJC of the front forefoot (i.e., lateral or to the right for a right-handed bowler). Therefore, a negative value indicates greater lateral rotation of the pelvis (i.e., more side-on at that event). However, not all bowlers bowled with the same technique and the bowlers' mean positions are presented in Figure 11.2.2.2. The arm effector at BR indicates that some bowlers released the ball in a negative position compared to a positive position. This means that the bowlers with a positive value bowled the ball in a lateral position to the shoulder, whilst a negative value indicates greater medial rotation of the trunk.

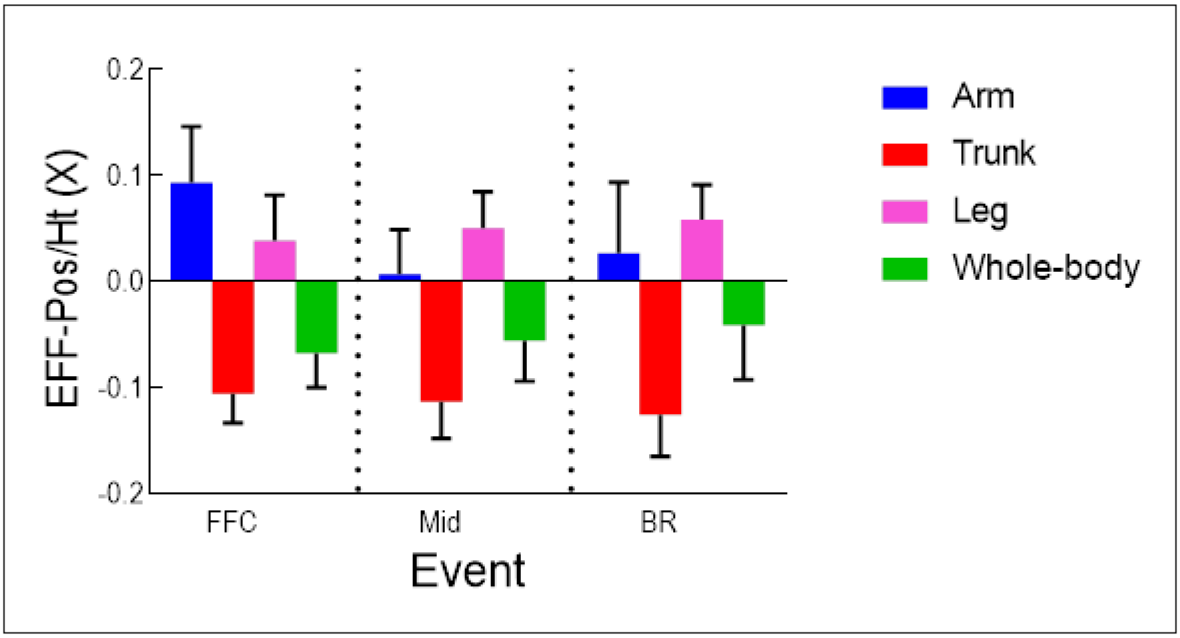

Figure 11.2.2.1: X-dimension group mean and standard deviation of height normalised effector position at FFC, Mid and BR events.

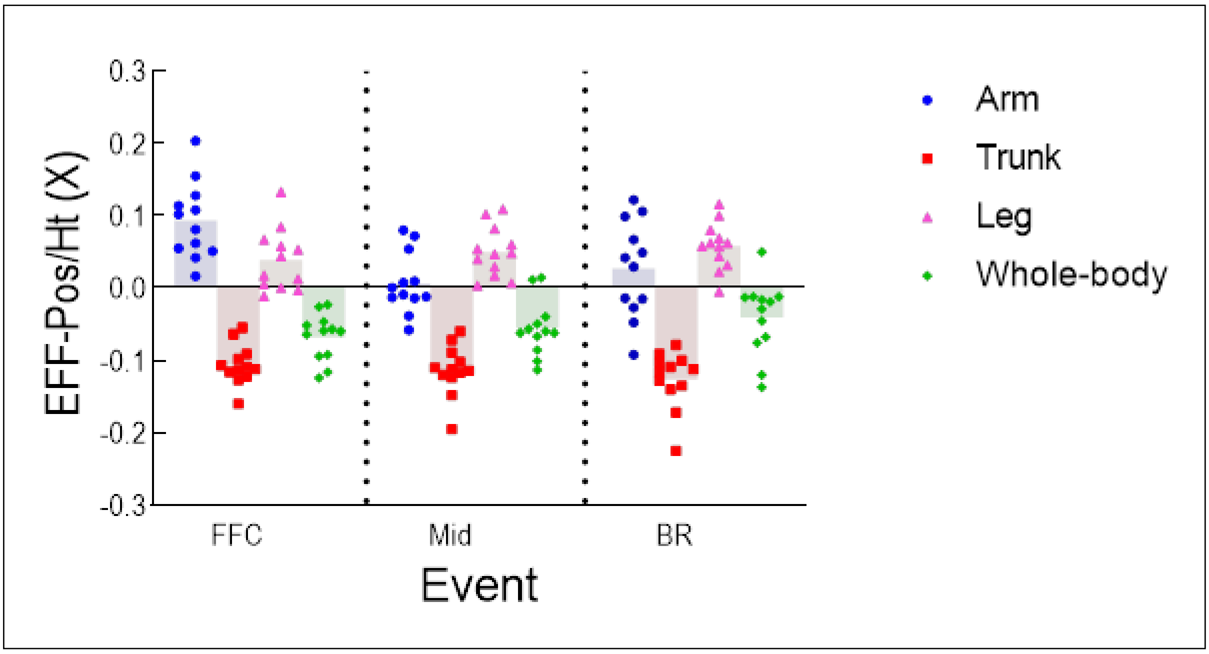

Figure 11.2.2.2: *X-dimension group mean and individual bowler distribution of height normalised effector position at FFC, Mid and BR events.*

In the Y-dimension, only the trunk at mid and BR events and arm at BR had a mean positive position (Figure 11.2.2.3). At BR, the mean position of the whole-body effector (-0.020) was almost exactly over the metatarsal phalangeal joint centre, with an overall individual distribution of hand position at BR both negatively and positively over the MPJC (Figure 11.2.2.4). The position of the whole-body effector in the y-dimension is largely controlled by the leg, as once FFC has been made the position of the pelvis in relation to the MPJC, variability remains low (Mean: FFC: -0.443; Mid: -0.338; BR: -0.249), only increasing by 0.194% of normalised body height from FFC to BR. This may indicate an element of freezing in anterior movement of the pelvis, likely associated with the bracing of the front leg.

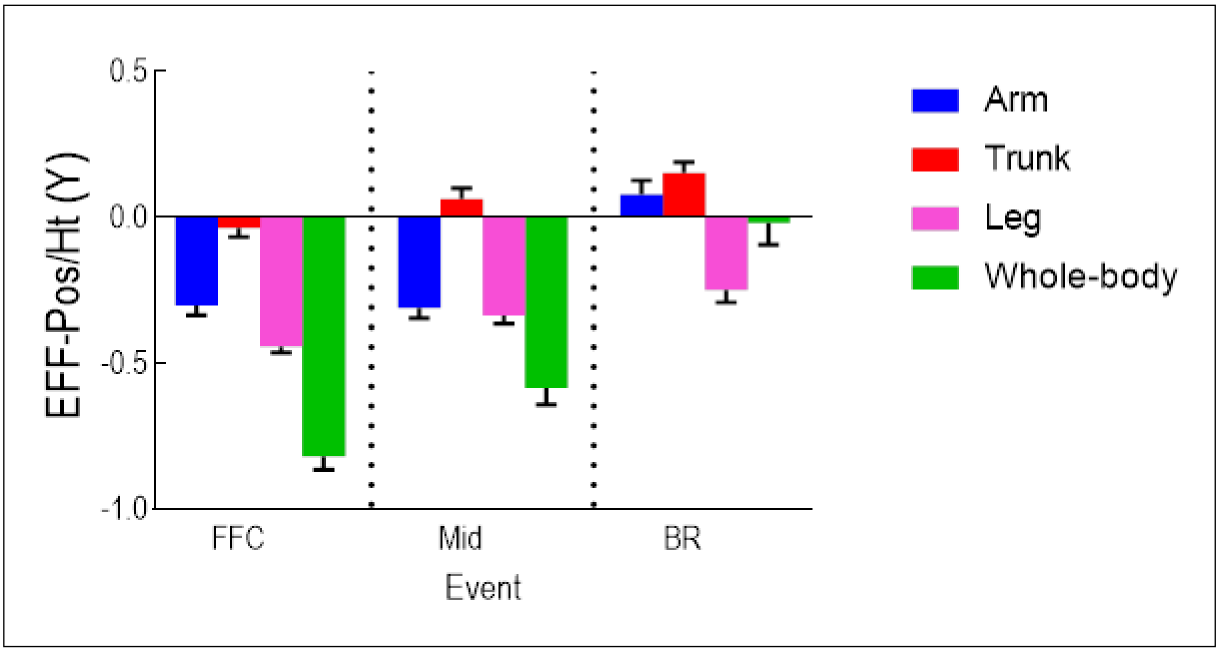

Figure 11.2.2.3: *Y-dimension group mean and standard deviation of height normalised effector position at FFC, Mid and BR events.*

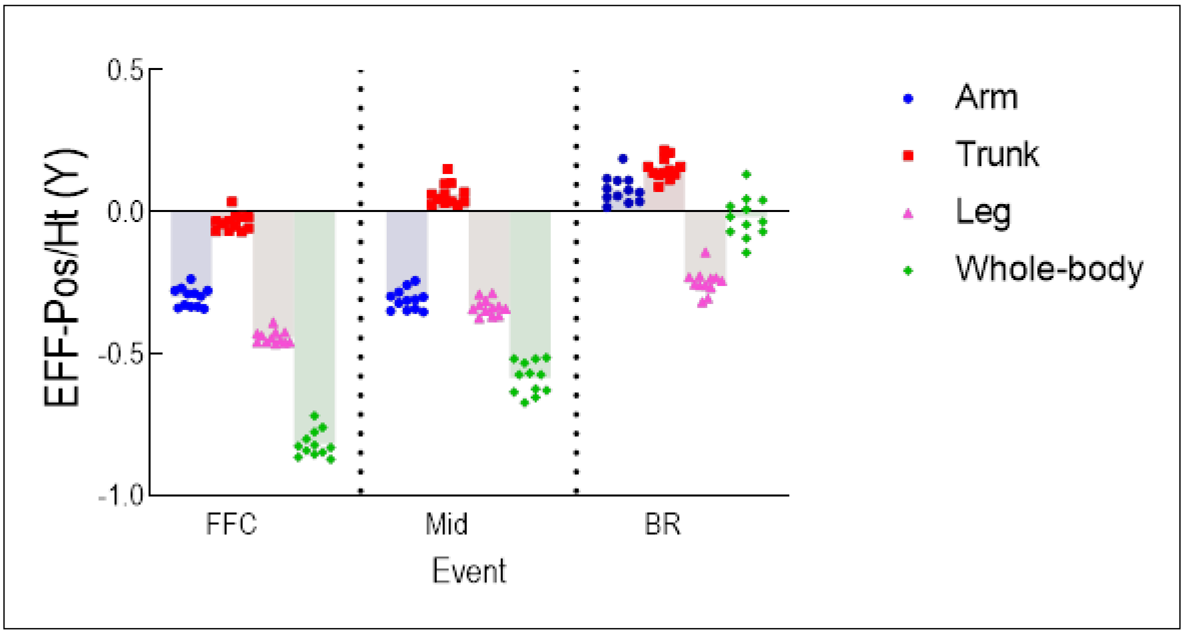

Figure 11.2.2.4: *The bar graph shows the Y-dimension group mean of height normalised effector position at FFC, Mid and BR events for all the bowlers and the coloured data points indicate the distribution of each individual bowler's position values.*

Figure 11.2.2.5 describes the effector group mean position and standard deviation of the Z-dimension. Results indicate the whole-body effector mean height grew across the three events. Height was likely influenced by the arm, as the effector position of both the leg and trunk variability remained comparatively low. However, whole-body effector variability lessened as the phase progressed as, at BR, variability (± 0.11) was less than compared to FFC variability (± 0.24). This is likely influenced by the straightening of the bowling arm through its circumduction to release.

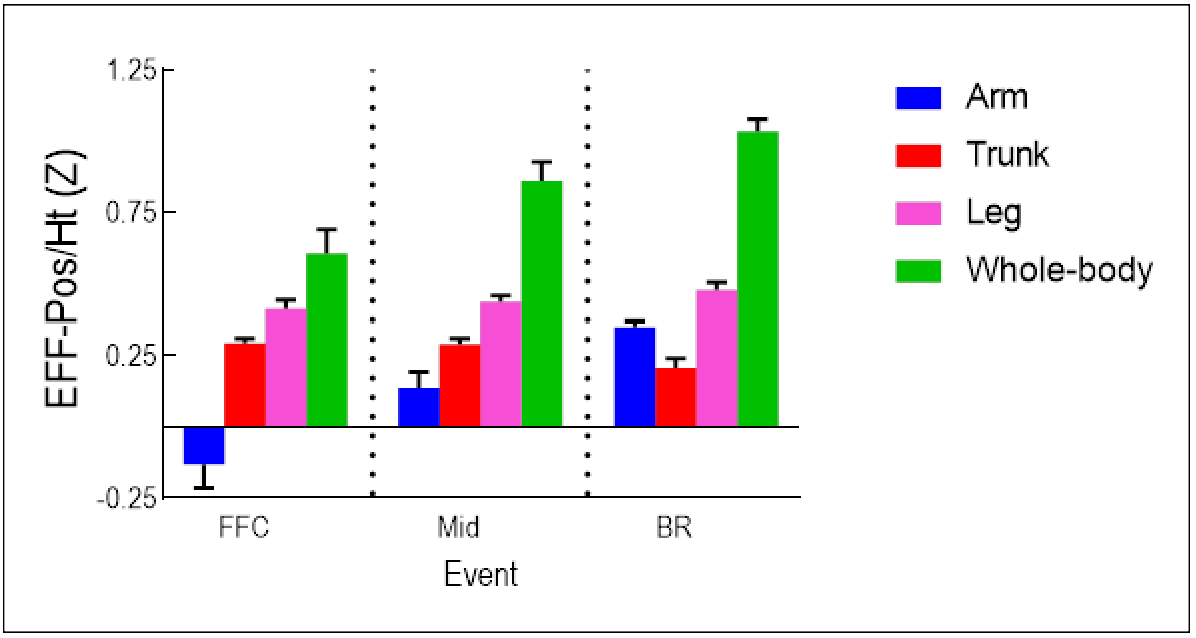

Figure 11.2.2.5: *Z-dimension group mean and standard deviation of height normalised effector position at FFC, Mid and BR events.*

11.2.3 Effector variability across the acceleration phase

Table 11.2.3.1 presents the effector variability for the three elemental effectors and whole-body effector across all dimensions. It was found that effector variability was relatively similar in value across all effectors, ranging between a standard deviation of 0.004 to 0.033. The lowest variability occurred in the leg at FFC in the Z-dimension and the highest standard deviation value at BR in the whole-body effector in the Y-dimension. Low variability of leg-Z at FFC indicates that bowlers were consistent at maintaining pelvis height throughout their stride length. High variability of the whole-body effector in the Y-dimension at BR, however, indicates limited control between all three elemental effectors in maintaining whole-body effector-Y endpoint variability. The only substantial changes in variability across the events (most notably mid to BR) were in the Y- and Z-dimensions, for both the arm and whole-body effectors. In contrast, the leg effector variability remained low only fluctuating slightly between a standard deviation value of 0.004 and 0.008 across the three events and dimensions. The leg effector was also the least variable of the three elemental effectors, while the whole-body effector was the most variable. However, collective error of the three elemental effectors indicates the whole-body effector produced less variability than the summed error. This result indicates there may be effector cooperation occurring between the elemental effectors to reduce whole-body effector variability (i.e., body posture variability).

Table 11.2.3.1: *Height normalised effector position group standard deviation values across the three dimensions at FFC, Mid and BR events. Bolded values are the most variable effector for each dimension at each event.*

Effector	X			Y			Z		
	FFC	Mid	BR	FFC	Mid	BR	FFC	Mid	BR
Arm	0.013	0.011	0.010	0.011	0.009	0.026	0.020	0.018	0.005
Leg	0.007	0.007	0.008	0.008	0.008	0.008	0.004	0.005	0.007
Trunk	0.012	0.012	0.013	0.009	0.010	0.012	0.009	0.009	0.010
Whole-body	**0.020**	**0.021**	**0.022**	**0.016**	**0.019**	**0.033**	**0.024**	**0.020**	**0.011**

Group mean effector variability of the acceleration phase is presented by Figure 11.2.3.1 and bowler mean effector variability is presented in Figure 11.2.3.2. Acceleration phase variability was taken as mean average of standard deviation across 11 time slices. Figure 11.2.3.1 shows the whole-body effector variability was more variable than the component elemental effector units (i.e., limbs). Variability of each effector at each time slice across the acceleration phase is shown in Figures 11.2.3.3, 11.2.3.4 and 11.2.3.5. Whole-body effectors variability progression is influenced by the arm as seen in the Y- and Z-dimensions. Across the X-dimension, variability remains mostly constant, apart from the arm effector which sees a slight decrease in variability as the acceleration phase progresses. In the Z-dimension, variability decreases in the arm and whole-body effector towards BR. However, variability increases for the leg and trunk at BR.

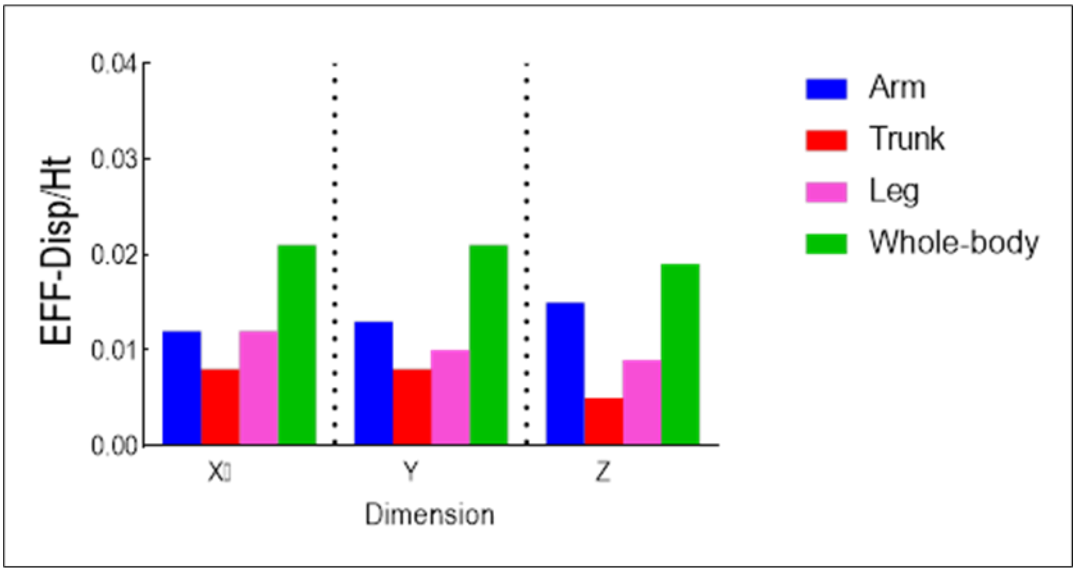

Figure 11.2.3.1: Mean of group effector displacement variability (standard deviation) from the time normalised acceleration phase.

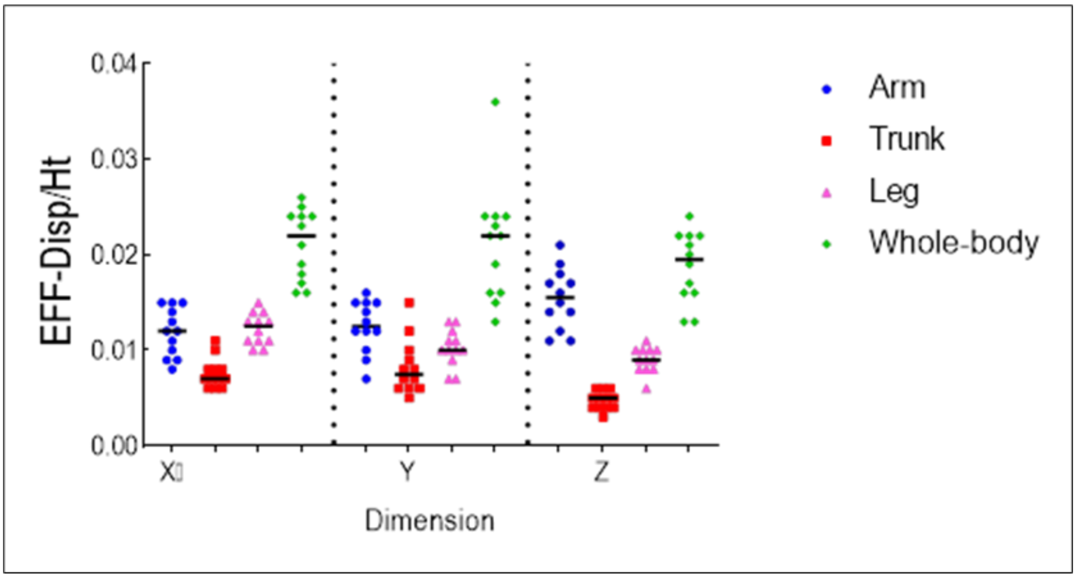

Figure 11.2.3.2: Bowler's mean effector displacement variability (standard deviation) and group mean effector standard deviation of the acceleration phase

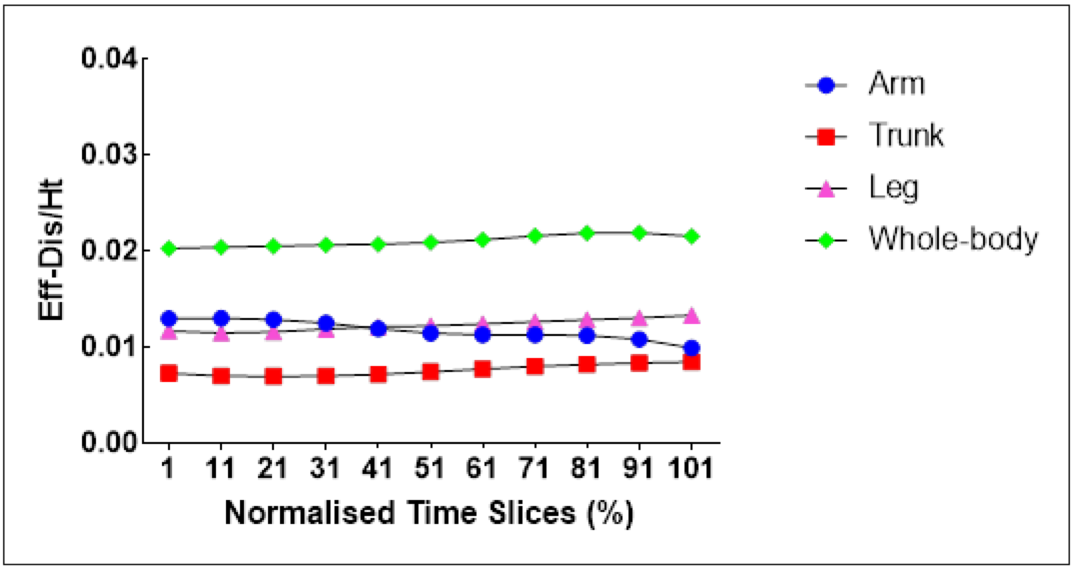

Figure 11.2.3.3: *X-dimension group mean effector displacement variability (standard deviation) at each tenth time slice normalised to 101 points.*

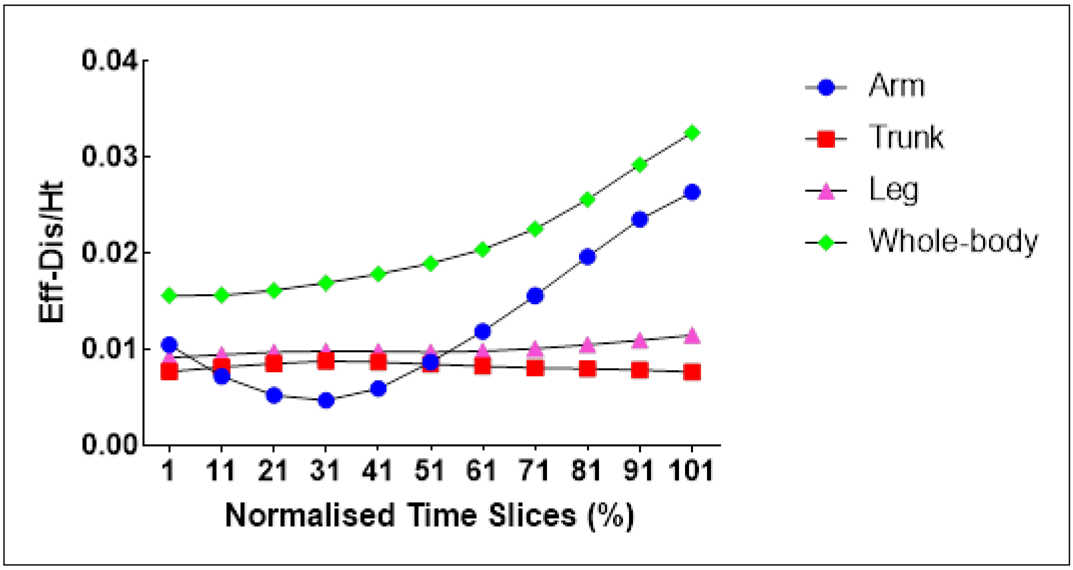

Figure 11.2.3.4: *Y-dimension group mean effector displacement variability (standard deviation) at each tenth time slice normalised to 101 points.*

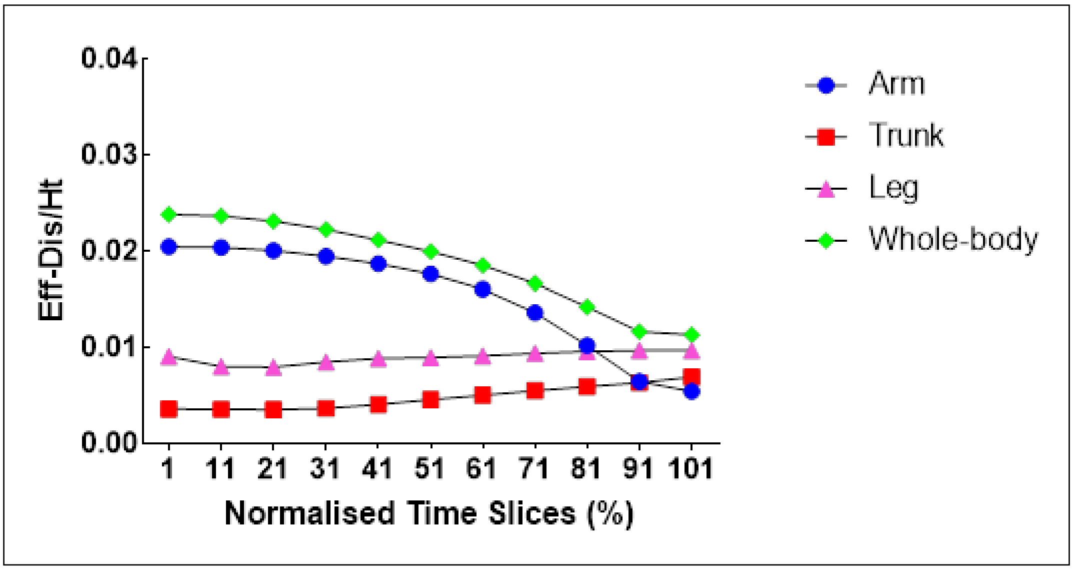

Figure 11.2.3.5: *Z-dimension group mean effector displacement variability (standard deviation) at each tenth time slice normalised to 101 points.*

11.3 Influence of effector variability on vertical velocity variability

Aim 3: What elemental effector, and in which dimension, explains vertical velocity variability?

Aim 1 established that VV_{BR} variability is the critical release parameter responsible for pitch length accuracy. In Aim 3, a regression analysis was used to investigate which effectors and their properties can predict the variability in VV_{BR}. A description of the mean group average of the three elemental effectors (independent variables) is provided in Table 11.3.1, as well as the nine properties used in the stepwise regression analysis. Each bowler's acceleration phase effector variability was used as an independent variable. The whole-body effector was not included as an independent variable because of likely multi-colinearity issues with other effectors, but more essentially, the purpose of the regression was to identify a model that explains which effector components (of bowling technique) are most responsible for vertical velocity control.

The stepwise regression analysis identified which of the components of the three elemental effectors predict VV_{BR} variability. The regression model included the trunk in the Z-dimension and leg in the X-dimension. The fitted regression model was the following - (p = 1.066 + -107.534 Trunk-Z + 45.713 Leg-X). The overall regression was statistically significant, being (R^2 = .849, F (2, 9) = 25.287, p = <.001). Trunk-Z was found to describe the following - (β = -107.534 t-(9) = -4.099, p = .003), while Leg-X effector was described as (β = 45.713, t-(9) = 3.302, p = 0.009). Individually, Trunk-Z made a larger unique contribution to describing VV_{BR} variability, with a negative coefficient of -.597 compared to the positive coefficient of Leg-X at .481.

Table 11.3.1: *Mean group effector displacement variability (standard deviation) during the acceleration phase. Bolded values are the most variable performed effector variability for each dimension.*

Effector	X	Y	Z
Arm	**0.012**	**0.013**	**0.015**
Leg	0.008	0.008	0.005
Trunk	**0.012**	0.010	0.009

11.4 Inter-effector cooperation

Aim 4: Is there evidence of inter-effector cooperation to control the whole-body effector?

A simulated cyclical shuffle of elemental effectors was used to find kinematic cooperation of the whole-body effector. The shuffle was used at three events (FFC, MID and BR). Figure 10.11.2.1 and Section 10.12.2 outlines and explains the process adopted. The mean value of each individual bowler's new simulated shuffled whole-body effector (S_WBEV) variable displacement from a single shuffled elemental effector (i.e., S_WBEV_{arm}-X) was then taken and the standard deviation of those eighteen trials were recorded and assessed against the bowler's performed unshuffled whole-body effector vector displacement (WBEV). Changes in S_WBEV displacement variability will explain two things. First, an increase in variability of the S_WBEV compared to the WBEV after the simulated shuffle (i.e., S_WBEV > WBEV), would indicate there is collective cooperation occurring between the elemental effectors to reduce whole-body effector variability, as body posture is controlled and performed better than if the bowlers produced their effector displacement values at random. However, if a decrease in variability of the S_WBEV compared to the WBEV (i.e., S_WBEV < WBEV) result was found, it would mean that an increase in whole-body effector variability may have a deliberate purpose in relation to performance. Alternatively, it is more likely large variations have minimal effect on performance, thus there is no need to control it. This is apparent in the Y-dimension.

Figure 11.4.1 contrasts the results of the surrogate S_WBEV variability compared to the WBEV in the X-dimension. The statistical results from a paired-sample t-test are indicated on Figure 11.4.1 and outlined in Table 11.4.1. They evaluate the difference significance between the S_WBEV-X and WBEV-X on group performance. The performed variability (WBEV-X) was found to be significantly lower than the surrogate data for all simulated effectors (S_WBEV-X), and at all three events of the acceleration bowling phase. This simulated result indicates the bowlers produced a smaller amount of effector displacement variability in the X-dimension than if they had performed it at random, an indication of kinematic cooperation. Of the effectors shuffled, the S_WBEV_{trunk} experienced the largest increase at each event, most notably at BR, increasing from a WBEV of 0.022, to a S_WBEV_{trunk} of 0.032. S_WBEV_{leg}-X was the next most variable effector across all three events (S_WBEV_{leg}: FFC = 0.027, Mid = 0.028, BR = 0.029). Leg-X was identified in the regression analysis as being important in describing VV_{BR} variability. This shuffle demonstrates kinematic cooperation is occurring to reduce whole-body effector variability amongst the effectors. As a result, the leg effector stability of the contralateral hip position to MPJC position after FFC is important for both release position posture control and vertical velocity control.

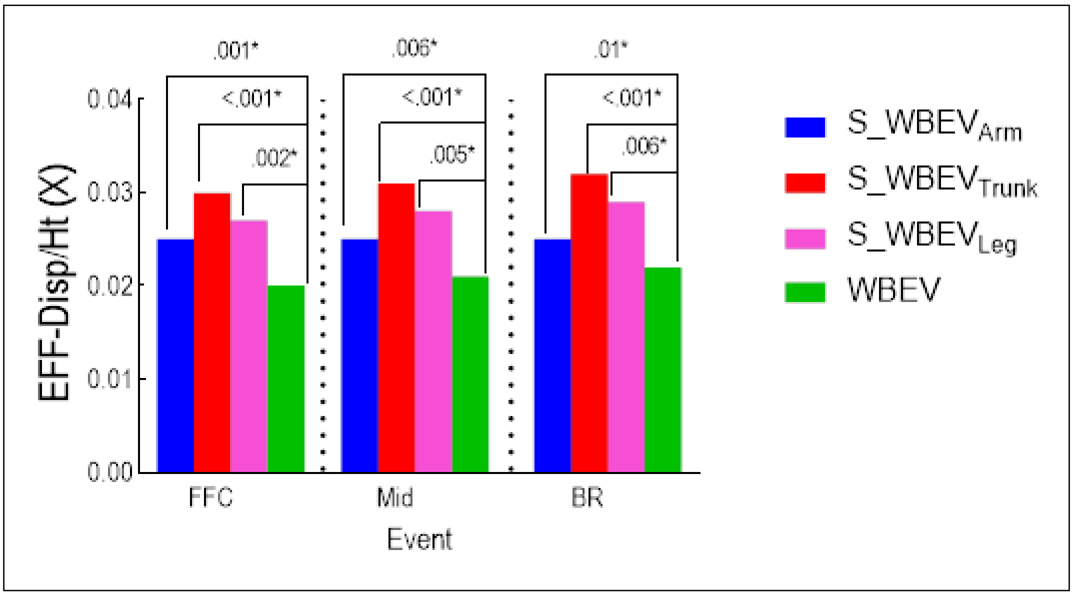

Figure 11.4.1: *Effector coordinated covariance test (effector shuffle) amongst height normalised whole-body effector displacement variability in the X-dimension. *Significant paired-samples t-test p-value score between S_WBEV-X and WBEV-X.*

Table 11.4.1: *Paired-samples t-test results from the simulated elemental effector shuffle in the X-dimension. Mean shuffle score presents the group mean value of the S_WBEV after the simulated shuffle of each elemental effector.*

Effector Shuffle	**Df**	**t**	**Sig. (2-tailed)**	**Mean S_WBEV Shuffle Score**	**95% Confidence Interval**		**Eta-squared**
					Lower	Upper	
Arm (FFC)	11	-4.09	.001	-0.007	-.011	-.004	.603
Trunk (FFC)	11	-6.51	<.001	-0.010	-.013	-.007	.794
Leg (FFC)	11	-4.30	.002	-0.007	-.011	-.003	.627
Arm (Mid)	11	-3.41	.006	-.004	-.011	-.003	.514
Trunk (Mid)	11	-6.54	<.001	-.010	-.013	-.007	.795
Leg (Mid)	11	-3.47	.005	-.007	-.007	-.001	.523
Arm (BR)	11	-3.13	.01	-0.004	-.007	-.001	.471
Trunk (BR)	11	-5.50	<.001	-0.011	-.015	-.006	.733
Leg (BR)	11	-3.40	.006	-0.007	-.012	-.003	.512

The results of the S_WBEV-Y variability compared to the WBEV-Y are contrasted in Figure 11.4.2. Unlike with the X-dimension, S_WBEV-Y variability did not increase for all effectors at each event compared to performed effector variability. Variability increased in the FFC and Mid events, but all three elemental effectors, once shuffled at BR, saw a reduction in variability post-shuffle. Of the three effectors, S_WBEV_{arm}-Y had the biggest decrease in variability at BR, decreasing the effector displacement variability from a WBEV-Y of 0.033 to a S_WBEV_{arm}-Y of 0.026. Paired samples t-testing found only S_WBEV_{arm}-Y at FFC were significant (p = .042, t (11) = -2.29). This result indicates that the hand position (endpoint), in relation to the shoulder (origin) in the Y-dimension at that event, may be important for this fast-bowling group.

Despite the arm at FFC indicating kinematic cooperation at FFC, the results from the Y-dimension shuffle and t-test scores indicate the bowlers are not adopting kinematic cooperation to control the whole-body effector variability in this dimension. In fact, at BR the bowlers' WBEV-Y is larger than the S_WBEV-Y for all three effectors. The bowlers' performed variability was being performed slightly worse than if they did it at random. A result of this nature means that this component of the bowling technique has minimal effect on the performance. Therefore, there is a limited need to control it by effector compensation.

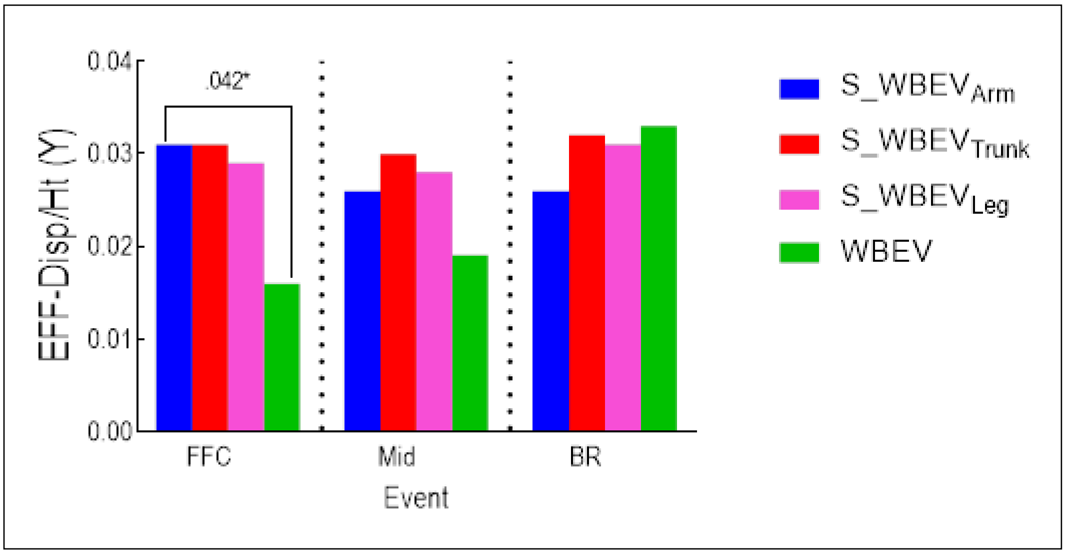

Figure 11.4.2: *Effector coordinated covariance test (effector shuffle) amongst height normalised whole-body effector displacement standard deviation in the Y-dimension. *Significant paired-samples t-test p-value score between S_WBEV-Y and WBEV-Y.*

WBEV-Z comparison to S_WBEV-Z is outlined in Figure 11.4.3. The shuffle produced similar displacement results to the X-dimension, which saw an increase in S_WBEV at all three events and effectors after the shuffle. The biggest change in S_WBEV-Z was at BR, increasing from a $WBEV_{leg}$-Z of 0.011 to a S_WBEV_{leg}-Z of 0.032, S_WBEV_{trunk}-Z of 0.029, and S_WBEV_{arm}-Z of 0.033. The

S_WBEV_{trunk}-Z was the least variable simulated effector at each event and the S_WBEV_{leg}-Z at BR produced a significant paired-samples t-test result (p = .038, t (11) = -2.36). All other variables were not deemed to be significant by the t-tests.

The results from the Z-dimension shuffle and paired-samples t-test indicate some compensatory effector control of the whole-body effector, with all simulated variability outputs resulting in an increase in S_WBEV. However, the most significant result was with the S_WBEV_{leg} indicating control of the contralateral hip height at BR amongst the bowling group. Interestingly, the S_WBEV_{trunk}-Z at the three events did not produce any significant t-test results. This is despite the Trunk-Z effector being identified in the regression model as being a significant contributor to vertical velocity control and the shuffle indicating the bowlers were better able to produce a less variable WBEV compared to the S_WBEV.

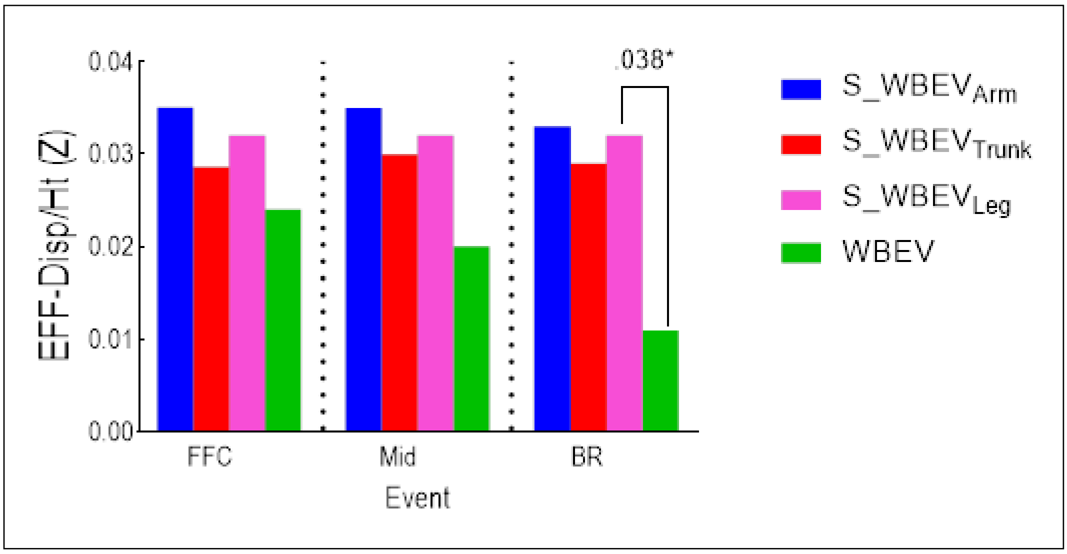

Figure 11.4.3: *Effector shuffle, height normalised whole-body effector displacement standard deviation in the Z-dimension. *Significant paired-samples t-test p-value score between S_WBEV-Z and WBEV-Z.*

12.0 Discussion

12.1 Release parameter coordination and pitch length variability

The general aim of this thesis was to investigate how bowlers are controlling pitch length. In this discussion, this thesis will explore which of four BR parameters is most responsible for controlling pitch length and assesses whether there was any covariance between parameters aiding in pitch length control.

12.1.1 Release parameter and pitch length variability

Pitch length control (i.e., accuracy) is determined by the consistency of the bowler to bowl their desired pitch length. In this study, the bowlers were found to be consistent to within a standard deviation of 1.89 m of their mean pitch length with respect to each bowler's mean pitch length location. This recorded accuracy of 1.89 m was slightly less accurate than previous documented pitch length accuracy of 1.76 m by Cork et al., (2013). However, the mean bowler pitch length of 6.12 m fell within the desired range of a good pitch length (6.0 – 8.0 m), and within only a few centimetres of the 6.15 m pitch length considered the best for performance (Harwood et al., 2019). To ascertain pitch length, a simple mechanical model of projectile motion was used to quantify how pitch length varies relative to changes in four BR parameters. The model ignored the presence of lift, spin and drag coefficients used in other cricket ball (Baker, 2010; Baker, 2013; Peploe et al., 2017) and baseball (Kusafuka et al., 2022) flight models. In fast bowling, the vertical flight path is not substantially affected by these force coefficients (Baker, 2010; Baker, 2013). Ignoring the influence of such parameters enabled relatively simple isolation and exploration of the effect each of the primary four BR parameters has on pitch length control; unlike other methods that recorded pitch length directly from the landing location on the cricket pitch surface (Ball & Hyrsomallis, 2012; Cork et al., 2013).

Regression analysis of release parameter variability showed the four combined release parameters determined 79% of pitch length variability. However, VV_{BR} variability was the only significant independent variable. This was not an unexpected result, as Kusafuka et al. (2022) and Harwood et al. (2018) both noted that BR angle, which is a ratio of vertical and horizontal velocity, played a role in explaining accuracy in baseball pitching vertical displacement and cricket fast bowling pitch length respectively. Horizontal speed had also previously shown little influence on vertical trajectories variance through varying fast bowling speed ranges (Baker., 2010). Despite VV_{BR} being the only significant independent variable in the regression equation, vertical release position of the ball was significant at the 94% confidence level. This may indicate a possible assistive nature of posture at release to VV_{BR} or accuracy. But the small cohort size of this study meant the significance of vertical release may not have been fully explored. Thus, the lack of significance of assisting parameters, besides a plausible assistive contribution of vertical release, the model suggests VV_{BR} is the prominent predictor and influencer on pitch length accuracy.

Despite the two-dimensional BR position being consistent amongst the bowling group with a group standard deviation of 0.02 m, it did not have an influence on pitch length accuracy. The lack of evidence surrounding BR positioning's influence on pitch length variability was not surprising, because a bowler's two-dimensional release position is deemed a constrained variable. The bowler's height constrains vertical release positioning and any minimal fluctuations, as highlighted by the small standard deviation of vertical positioning of 0.02 m. This will have a limited influence on flight time and range, as demonstrated by Dupuy et al. (2000) in underarm throwing. Horizontal release position is also constrained by the bowling crease under the laws of cricket. For instance, a penalty will apply when over-stepping the bowling crease and if the bowler bowls further back it will allow the batter more time to react. Therefore, there is no advantage in increasing the variability of the H_{RP} on performance and its effect on length control. Even in junior fast bowlers tasked with bowling different pitch lengths, there is no indication of adaptive change in foot position to change their pitch length (Harwood et al., 2018). The minimal change in horizontal release positioning of 0.14 m found here supports this result. Therefore, the constrained nature of horizontal and vertical release position (body posture) is not actively adapted to bowl a consistent pitch length.

Reproducibility of vertical velocity, therefore, is the most critical parameter in controlling pitch length accuracy. Reproducibility, or the reduction of variability, of a parameter has not necessarily been seen as important in improving accuracy in throwing, as shown in previous two-dimensional throwing tasks (Kudo et al., 2000; Nasu et al., 2014; Cohen & Sternad, 2009). Improvement in two-dimensional throwing performance accuracy was more likely a result of improved compensatory coordination amongst the release parameters (Kudo et al., 2000) and even in late stages of practice skilled subjects continue to improve because of increased covariation (Cohen & Sternad., 2012). Even though cricket fast bowling action doesn't follow the same biomechanical action as throwing it does share similar projectile and goal outcomes. Thus, it would hypothetically follow a similar principle. However, it appears to oppose that research and leans towards improved reproducibility of release parameters (i.e., VV_{BR}) being more beneficial in achieving a more accurate pitch length.

12.1.2 Mean absolute vertical velocity error and pitch length

Vertical velocity may be the most critical determinant of pitch length control. However, its influence may also change between different pitch lengths. Further analysis of vertical velocity control obtained from the shuffle explored the possibility of correlations between the more accurate and less accurate bowlers' ability to achieve the required VV_{BR} needed to bowl at their goal length. As a group, to bowl at their mean pitch length of 6.12 m the bowlers needed to achieve an average release vertical velocity of -3.85 $m.s^{-1}$. They were found to have a mean absolute error of 0.93 $m.s^{-1}$ from achieving that required velocity. Individually, 5 of the 6 most accurate bowlers (not bowler 4) produced a mean absolute error better than (less than) the group mean absolute error. The opposite was true for the 6 least accurate bowlers with only bowler 7 producing a mean absolute error less than 0.93 $m.s^{-1}$ (Appendix 18.1). A correlation plot (Appendix 18.2) between mean absolute error and performed accuracy (pitch length standard deviation) found an insignificant strength correlation ($R^2 = .252$, $p = .960$) between the bowlers with less absolute vertical velocity error and more consistent pitch length accuracy. It was thought bowler 4 may be an outlier as their mean pitch length (8.29 m) was shorter than the expected good pitch length, thus a Grubbs' test was conducted on mean average pitch length. However, the Grubbs' test found that bowler 4 did not meet the exclusionary criteria ($Z = 2.412$), marginally failing to do so ($Z = 2.184$, $p > 0.05$). Yet, when the correlation (Appendix 18.2) was performed again with the suspected outlier removed (bowler 4), it produced a strong positive correlation between absolute error and pitch length variance ($R^2 = .693$). Future research could look at investigating the link between these two variables, as this study could not adequately determine the correlation between vertical velocity mean absolute error and pitch length control.

Despite no correlation being determined, the adjusted results of bowler 4 may add support to accuracy results obtained by Phillips et al. (2012) in future research. Phillips et al. (2012) found that, regardless of cricket fast bowling expertise, accuracy was harder to maintain when bowling a fuller length compared to a shorter length. This may be due to VV_{BR} variability having a greater influence on pitch length accuracy over the course of a more prolonged ball flight. Therefore, control of VV_{BR} variability may not be deemed as necessary for accuracy when bowling shorter lengths. In underarm throwing, release angle was greatly influenced by distance (Dupuy et al., 2000). Thus, the more flight distance required, the more likely variability will have a greater impact on the accuracy outcome. For instance, bowler 4's mean pitch length was considerably shorter (8.29 m) than the group's mean (6.12 m). Despite bowler 4 producing a consistent pitch length (± 1.72 m), bowler 4 produced a larger mean absolute vertical velocity error of 1.12 $m.s^{-1}$ compared to the group mean of 0.93 $m.s^{-1}$. This is possibly due to bowler 4's natural good length being shorter and VV_{BR} having a greater influence over both flight time and direction. However, further research is needed to investigate the influence of VV_{BR} variability on pitch length accuracy in cricket fast bowling over different set pitch lengths and in differing levels of expertise.

12.1.3 Release parameter coordination

To ascertain whether improving the reproducibility of release parameters is beneficial to achieving a more consistent pitch length accuracy, assessment of whether compensatory covariation is occurring between release parameters needed to be investigated. Just like the nine release parameters in baseball pitching used by Kusafuka et al. (2020), there are numerous combinations of release parameter values that achieve the same pitch length location in cricket fast bowling. Thus, it is conceivable a bowler can produce a varied range of combinations of parameter values to achieve the pitch length. Pitch length accuracy could then be theoretically controlled by the compensatory coordination of multiple release parameter values to maintain the same outcome (i.e., faster horizontal release velocity could be controlled by a change in vertical release velocity). To investigate this coordinated covariation of the release parameter system, a cyclical parameter shuffle was adopted, and an index of cooperation was employed to ascertain cooperation influence of other variables on pitch length accuracy. A singular shuffle of a specific parameter, as conducted here, captures the relationship and overall coordinative contribution between one parameter on the other components (Kusafuka et al., 2022). Thus, this method of analysis could investigate the individual contribution each parameter has on the redundancy of the BR system. If a parameter was to have a significant impact on the performance outcome of pitch length variability, while influencing other key parameters, a change in overall pitch length variability and Index of Cooperation scores would be seen.

The release parameter shuffle identified there was a lack of evident covariation between the BR parameters in controlling pitch length. That was because the derived Index of Cooperation scores indicated no clear distinction between the performed and shuffled pitch length variance producing IoC values all close to one. In baseball pitching, Kusafuka et al. (2022) found similar results with vertical displacement, whereby the recorded IoC found mean horizontal velocity and mean pitch release angle were similarly close to one. This IoC score should be regarded as an overall expression of cooperative contribution to the degree of variability, with a score close to one revealing there to be no distinction between the performed and simulated shuffle results (Kusafuka et al., 2022). Thus, this performed shuffle revealed no indication of coordinated covariation between any of the four release parameters, as there was no distinction in Index of Cooperation scores as a collective group. This result was likewise found by Kusafuka et al. (2022), where baseball pitching vertical displacement was likely improved by reproducibility and not by coordinated co-variability, and in basketball free throws, whereby, reproducibility of release parameters was more beneficial to performance than coordination (Nakano et al., 2022). In fact, the cooperative contribution results produced in this study were weaker than those obtained by Kusafuka et al. (2022), indicating reproducibility may be even more beneficial in maintain length control in fast bowling than compared to baseball pitching.

The lack of covariation between BR parameters could also be a result of a hierarchy of importance between the release parameters and the need to maintain a fast release speed. A sensitivity analysis, assessing the change of one standard deviation in any of the four release parameters showed that VV_{BR} produced the greatest change in mean pitch length (Table 11.1.4). This demonstrated VV_{BR} had a disproportionate influence on pitch length compared to the other three release parameters. Thus, IoC scores investigating covariation may not be able to fully express this mechanism, as some individual bowlers may have still utilised that mechanism to control their length. Individual shuffle analysis showed that some bowlers produced IoC scores greater than one and it is plausible that these bowlers still utilised some form of coordinated covariation to aid accuracy (Table 11.1.5). Some baseball pitchers were also found to produce greater IoC values too, but the results were more pronounced when pitching slower balls compared to fast balls (Kusafuka et al., 2022). Kusafuka et al. (2020) baseball pitching results showed in different speed deliveries vertical pitch location was more greatly affected by coordinated covariation of release angle and horizontal speed in slow pitches compared to fast pitches. Kusafuka et al. (2022) noted the need for speed may be a reason why faster pitches had less coordinated covariation. This may also be the case with the cricket fast bowling as they too are bowling at similarly high velocities. At that high-speed, VV_{BR} is likely the dominant determinant of pitch length, thus any covariance could be masked by its influence. However, as indicated by some individual IoC scores, some bowlers may have been bowling at a sub-maximum speed allowing for the utilisation of coordinated covariation. Further studies would be needed to investigate this topic in cricket fast bowling specifically.

Another reason why cricket fast bowlers may not have used coordinated covariation to maintain pitch length is the high ground reaction forces experienced upon FFC. Cricket fast bowlers are known to endure high ground reaction forces through their braced front leg (Worthington et al., 2013b; Callaghan et al., 2021). It is also thought that bowlers transfer this ground reaction force (breaking force) generated from the linear kinetic energy of their run-up through segmental sequencing of movements (Ferdinands et al., 2013; King et al., 2016). This transference of energy would likely be prioritised for speed production as front leg breaking force has been linked to improved speed production (Wormgoor et al., 2010), yet it would likely instil instability within the bowler's effector system. Thus, a large force may require the bowler to control their body posture and balance at the bowling crease to generate speed and, as such, overlook release parameter covariation. However, the implications of ground reaction forces on accuracy, release parameter covariation and posture control were not investigated within this study.

This primary investigation uncovered that vertical velocity is the major influence on pitch length control. Indeed, pitch length control does not seem to be maintained by a system of coordinated covariation as with two-dimensional throwing tasks. It is, instead, more akin to baseball pitching vertical displacement control, whereby the majority of pitch length accuracy is most likely improved by reproducibility of vertical release angle in baseball pitches. However, further research is needed to investigate whether vertical velocity control remains important across accuracy of differing skill levels, speed, and pitch lengths.

12.2 ***Nature of effector variability***

This section will explore the nature of effector variability across the acceleration phase.

The aim of this sub-question was to investigate the degree of kinematic variability the effector system encounters in the bowling action. To date, kinematic variability of the effector system adopted in this study has yet to be explored in cricket fast bowling. An effector system is simply a redundant system that comprises joints and muscles, and muscles spanning a chain of segments that collectively have a functional purpose and common movement goal (Diedrichsen et al., 2010). It is believed cricket fast bowling is a highly variable and complex movement, as it encompasses many DoF and moves through considerable ranges of motion (i.e., arm circumduction), as well as experiencing large forces (i.e., ground reaction forces) (Perrett et al., 2020; Bayne et al., 2016). Therefore, there are many ways a bowler theoretically can produce their bowling action through the wide array of intra- and inter-effector movements. To explore kinematic variability, effector displacement standard deviations between the bowler's trials were recorded across the whole acceleration phase and at key events (FFC, Mid, BR). It was hypothesised that the whole-body effector variability could be greater than the variability found within each elemental effector in all dimensions throughout the acceleration phase. It was also hypothesised kinematic variability would change throughout stages of the acceleration phase.

12.2.1 Effector displacement across the acceleration phase

Time normalised effector displacement waveforms present the displacement path each effector travelled. Observationally, it is evident between the subject's mean whole-body effector endpoint that paths follow a similar path trajectory in both the Y- and Z-dimensions. This is not surprising as the cricket bowling action is restrained, through constrained technique requirements (i.e., straight bowling arm and bowling above shoulder height). Figure 10.2.4 indicates bowling arm effector contributes the most to whole-body effector displacement in these two dimensions. However, it is evident that there is an array of differences in the displacement path travelled by the whole-body effector. For instance, height of the whole-body effector normalised to body height at FFC for one bowler was 0.54 and at BR the hand was at 0.94. The height of the whole-body effector at BR indicates this bowler's hand (i.e., effector height) was below standing height. However, another bowler's whole-body effector height at FFC was 0.72 and at BR increased to 1.06 (i.e., ball is released above standing height). This indicates there are significant differences in bowling technique classes adopted amongst the bowling cohort.

The differences are more noticeable in the X-dimension of the whole-body effector displacement waveforms. For some bowlers, their technique starts in a lateral position (i.e., positive X-dimension) (0.09) at FFC before travelling in a medial direction (i.e., negative X-dimension) to BR (-0.14). This type of movement pattern indicates that they were likely in an upright position at FFC (as their MPJC is positioned more medially than is their hand), before a large lateral flexion of the trunk and other effector movements resulted in a more front on and medial position at BR (i.e., hand more medial than MPJC). In contrast, another bowler's technique started in a medial position (-0.08), before finishing in a more lateral position than at FFC (-0.02). Shoulder counter-rotation and/or pelvis-shoulder separation angle is the likely cause of the medial position. The mixed bowling action, for instance, is associated with large shoulder counter-rotation and is defined by its angle at BFC (Ferdinands et al., 2014). Front-on bowlers, however, do not exhibit the same amount of shoulder counter rotation (Ferdinands et al., 2014) and would likely not produce such a medial whole-body effector X position at FFC. The displacement differences of the X-dimension likely indicate variations in technique adopted amongst the bowlers.

Although bowlers were selected from a similar cohort (i.e., bowling ability and age), technique type was not a requirement, nor was it determined for any of the bowlers in this study. As such, differences in effector displacement positioning or effector variability were not assessed between different bowling techniques. It may be an option for further research on bowling technique understanding to investigate the changes in effector displacement across the whole-bowling action, as it may lead to an understanding of preferred movement pathways for each technique.

12.2.2 Effector variability at events and across the acceleration phase

Effector variability at events was presented as a standard deviation. Variability of each effector and dimension was expressed for the three key events identified for analysis during the acceleration phase.

Variability of the whole-body effector was found to be the most variable parameter across the three events and dimensions (Table 11.2.3.1). However, in the X-dimension (i.e., medial lateral dimension), variability remains low with little fluctuation in variability at each event (at FFC arm = 0.013, leg = 0.007, trunk = 0.012; at Mid arm 0.011, leg = 0.007, trunk = 0.012; at BR arm = 0.010, leg = 0.008, trunk = 0.013). Only between FFC and BR does variability see the biggest change in standard deviation from 0.020 to 0.022. This indicates that the whole-body's variability did not change greatly throughout the acceleration phase. Whole-body effector's variability is calculated from the hand position to MPJC of the forefoot. Although, as the observations of the different bowling techniques adopted by the bowling cohort and movement patterns are vastly different between bowlers, the mean subject variability in the X-dimension does not alter greatly between each event.

In contrast, variability of the Z- and Y-dimensions changed by more than 100% from FFC to BR. However, that change was not uniform in direction. The Y-dimension saw the whole-body effectors variability increase towards BR, whilst it decreased in the Z-dimension. The difference in variability of the Y- and Z-dimension is consistent with BR parameter variability (i.e., release position). Intra-participant variability of release position results has indicated release height is less variable than horizontal release position (Harwood et al., 2018). Whole-body effector variability is largely influenced by the arm, as can be observed across the entirety of the acceleration phase (Figure 10.2.13 & Figure 10.2.14). The arm can also explain endpoint variability of the WB-Z effector at BR being likely reduced, as the arm is extended vertically at that point and is, thus, anatomically constrained.

Elemental effector variability was found to be less variable than the whole-body effector. The arm effector observed the largest changes in variability across each dimension amongst the elemental effectors. This is not an unexpected result as the arm effector goes through the largest range of motion (i.e., arm circumduction) and rotational velocity during the acceleration phase. It also explains the biggest influence on whole-body effector variability. Variability of the arm in the X- and Z-dimensions decreased from FFC to BR. The reduction in variability in the Z-dimension, as stated earlier with the whole-body, is likely a result of the arm being constrained by the extended elbow required to legally bowl a cricket ball. The position of the effectors origin and endpoint will be influenced by these joints and muscles controlling the joint movements. However, at BR, not only is the arm extended, it will also be parallel to the dimension it is in (i.e., Z). These two factors will reduce the number of DoF in that effector system. Resultingly, variability decreased for Arm-Z towards BR. However, the reduction of variability in the X-dimension and increase in variability in the Y- is less obvious across the acceleration phase.

In motor control, understanding how coordination and kinematic control of movements are modified during motor learning is one of the key concerns of the area (McDonald et al., 1989). Variability arises from external (i.e., mechanical or non-mechanical) and internal noise (sensorimotor) perturbations (Faisal et al., 2008). Even though the effectors are analysed separately, they are all contributing together to achieve the same outcome (i.e., deliver the ball accurately and with speed), and are all controlled by a single effector system (central nervous system). As Latash (2012) states, even simple tasks such as reaching for a target require multiple segments to create torque around one joint, typically involving several muscles that span it. The central nervous system (i.e., sensorimotor) seems to create a movement path throughout a choice of infinite possibilities (Latash, 2012). For such a complex multi-effector movement, bowling would involve numerous combinations and DoF at each level. This variability would likely change throughout the acceleration phase as previously demonstrated in handball throws (Wagner et al., 2012).

In the case of the arm effector's Y-dimension, variability initially decreased to the 30%-point mark of the acceleration phase, before increasing substantially. At BR, the bowling arm is yet to be fully extended and elbow flexion is still present. However, from the 30%-point mark, the arm is likely to be fully extended for all bowlers. Just as the arm at BR in Z- is perpendicular, the Y-position of the arm shall be parallel in the Y-dimension at this point. However, from that point forward variability increases. As the arm remains locked in an extended position at the elbow, changes in effector length will likely be from alterations in effector origin position of the shoulder. The shoulder position will be influenced by the flexion, contraction, concentric contraction of the major (i.e., trapezius, deltoid & pectoralis major) and minor (i.e., teres minor and subscapularis) muscles that are employed by the bowler to complete the arm circumduction. These will all influence the DoF of the arm in the Y-dimension.

For the arm in the X-dimension, variability remained relatively consistent, only reducing a little from 0.013 at FFC to 0.010 at BR. As is the case for the Y-dimension, the muscles around the shoulder will influence the number of DoF in this dimension. However, it is somewhat dissimilar to the other two dimensions, as the variability of X- will be occurring around different effector positions, depending on the technique of the bowler. Figure 10.2.6 outlines the position of the arm at the three events and it can be observed that some bowlers operate through a more medial movement plane compared to the more lateral plane of others.

The leg and trunk effectors have the most anatomical DoF and motor complexity to achieve control over the effector endpoint position. Bernstein (1967) originally stated that the classic problem of redundancy posits a solution to motor learning, whereby the mastering of DoF through a strategy to reduce (i.e., freeze) it in the effector system to the minimum required, provides 'repetition without repetition'. Subsequent research has suggested the freezing by the DoF strategy of reducing variability is related to the learning level of the task, with the more complex the task the greater amount of reorganisation of DoF needed for it to be evidenced (Guimarães et al., 2020). An indication of the task complexity to control these effector positions could be that the trunk and leg effector variability showed an increase from FFC to BR across all dimensions. Effector variability is contributed to by perturbations arising from large ground reaction forces, rotational inertia through the trunk and signal dependent noise (Harris and Wolpert, 1998), due to the need to produce large muscle forces to transfer energy between effector systems. As this may apply particularly during the learning phase of the task, other motor control theorists have seen DoF as a positive for performance and learning.

The principle of abundance (Gelfand and Latash 1998; Latash, 2012) suggests that instead of reducing the number of solutions (i.e., DoF) into one single combination, the central nervous system can select multiple paths and produce many solutions. It could be argued that the increase in variability from FFC to BR in Trunk-Z, is the body exploiting motor redundancy to produce numerous kinematic solutions (Rosenblatt et al., 2014). This exploitation in redundancy leads to the desired endpoint trajectory of the effector needed to complete the task (Rosenblatt et al., 2014).

The purpose of this aim was to establish the degree of variability in the acceleration phase. It is evident that there are numerous DoF found in each effector and dimension as fast bowling is a complex motor control action that faces many perturbations. The whole-body effector was found to be the most variable of the effectors across the phase regardless of dimension. However, the variability is not uniform throughout the acceleration phase. In some cases, variability either increased or decreased towards BR in both the whole-body and elemental effectors. This is an indication of the body moving between an abundant system of DoF and a system whereby some DoF may be frozen towards BR when variability is decreased.

12.3 Kinematic effector control of vertical velocity variability

This section will explore the components of elemental effectors contributing towards vertical velocity variability and the likely mechanisms behind kinematic variability, in cricket fast bowling.

Investigation on the influence of variability of BR parameters on pitch length control concluded VV_{BR} variability was the most influential component. To date, no cricket fast bowling research has investigated a link between effector systems variability and VV_{BR} variability. For a bowler to control release parameters to reliably target a goal length (i.e., good length), it is theorised to require stabilisation of body posture, coordination of the central nervous system and motor proficiency of the effector system. Previously, in throwing, it has been reported that kinematic variability may be compensatory and may help reduce release parameter variability (Wagner et al., 2012). It is hypothesised that variability of the effector systems is compensatory in reducing VV_{BR} variability in cricket fast bowlers.

A stepwise regression analysis identified that Leg-X and Trunk-Z acceleration phase variability, from the three elemental effectors' components (i.e., dimensions), significantly accounted for 85% of the total variability in VV_{BR}, with a greater than 95% confidence level. Trunk-Z provided an independent negative contribution of -.597, whilst Leg-X provided a positive contribution of .481.

Variability in Leg-X comprises of fluctuations in lateral and medial contra-lateral hip joint location. This variability could arise from differences in hip flexion, trail leg hip rotation and balance of the braced front leg from ground reaction forces, as it lengthens and shortens the effector. Cricket fast bowlers encounter large vertical ground reaction forces at FFC and BR (Worthington et al., 2013b; Callaghan et al., 2021; McGrath et al., 2022). Peak ground reaction forces occur in the first 50 ms after FFC (Worthington et al., 2013b). The time to complete a bowling action from FFC to BR has been found to be 103 ms (Felton et al., 2019) and 110 ms in this study. Once peak force has been experienced the bowler is half-way through their acceleration phase, this could be a pivotal point of the bowling action where disturbances from ground reaction forces peak. This would likely affect the balance of the front leg, affecting the medial and/or lateral contra-lateral hip joint position.

Ground reaction forces are influenced by a few mechanical mechanisms. Quicker run-up speed has been associated with higher peak forces in both vertical and horizontal braking forces (Worthington et al., 2013b). However, the best individual predictor of ground reaction forces is plant angle of the front foot (Worthington et al., 2013b). Worthington et al. (2013b) speculated that having an aligned front leg and trunk would result in a greater ground reaction force, as there would be less hip flexion at FFC. Less hip flexion at FFC would likely lead to less compression of the hip that can act as a shock absorber and reduce the effect of the force. More hip flexion and/or control of hip flexion from the adaption of the front foot plant angle will theoretically result in less Leg-X variability, as the position and tilt of the pelvis through the acceleration phase movement will be maintained. In this study, Leg-X variability was found to have a positive contribution to VV_{BR} variability. Therefore, having less variability in Leg-X is likely more beneficial to performance (i.e., pitch length accuracy). Thus, front foot plant angle likely influences the leg effector's lateral and medial variability as well other joints within the effector system.

If ground reaction forces are large, perturbations can flow through the body affecting other intra-effector components. For instance, Worthington et al. (2013b) observed that some bowlers, in response to increasing ground reaction forces, flexed their front knee. Typically, bowlers intend to maintain an extended front knee for performance benefits (Worthington et al., 2013a), but some were unable to withstand the forces exerted and as result had to compromise and flex their knee (Worthington et al., 2013b). An extended front knee is believed to be an important bowling technique as it is linked to higher BR speed (Wormgoor et al., 2010; Worthington et al., 2013a). At extension, it acts as a breaking force allowing efficient transference of linear momentum to angular momentum (Wormgoor et al., 2010). For bowlers, an extended front knee will likely allow them to bowl faster, but large forces can be transferred through the body, unbalancing the effector system. As the longer effector length is more rigid (i.e., knee extended) the body must rotate around it more and the force will be converted through the rotation of the pelvis. The opposite though must also be true. If the knee is slightly flexed, it can absorb some of that ground reaction force and reduce the instability in the hip position. This is where the conundrum of speed versus ground reaction forces trade-off comes in, and by extension pitch length control; as it has been suggested that bowler's trade-off speed and ground reaction forces, with the fastest bowlers experiencing the highest peak forces and loading rates (Portus et al., 2004). On one hand, bowlers have an important technique component that will allow them to bowl faster but will also increase lower body instability through the development of high ground reaction forces. However, King et al. (2016) found no significant evidence of there being a relationship between ball speed and peak ground reaction forces, instead it appeared to come from a large braking impulse. This horizontal impulse was found to be strongly correlated with front foot plant angle, with 50% of the variation in impulse being explained by it (King et al., 2016). Once the front foot makes ground contact, it stops moving and the body rotates about the foot creating angular momentum (King et al., 2016). This increased angular momentum about the stationary foot will likely influence Leg-X variability, as the pelvis will undergo large rotational forces on top of the ground reaction forces. These two influencing mechanisms will instil more instability through the lower body (Leg-X) making it harder to maintain VV_{BR} (i.e., pitch length control).

The influence of ground reaction forces on Leg-X effector variability requires further investigation to determine the true extent of vertical and/or horizontal ground reaction forces effect on effector and VV_{BR} variability. Furthermore, it is important to note there will be an optimum technique (i.e., inter-joint coordination pattern) to control vertical velocity within the Leg-X effector system. As it is evident through both King et al. (2016) and Felton et al. (2020) that front foot plant angle and knee angle, for instance, both contribute to ground reaction force and horizontal impulses. In fact, a simulated cricket bowling model determined that the ankle and knee remained more extended in the optimal technique and that will specifically increase horizontal ground reaction forces (Felton et al., 2020). In the future, it is expected theoretical models will be able to explain the relationship between this and vertical velocity control in more detail.

Trunk-Z variability was determined as a negatively associated influencing variable in determining VV_{BR} variability. Trunk-Z variability arises from perturbations in maintenance of the bowling shoulder height throughout the acceleration phase. Trunk effector length is likely influenced by bowling technique mechanisms (i.e., trunk flexion), ground reaction forces and proximal to distal sequencing of kinetic energy, as flexion of the trunk will reduce that vertical length between the contralateral hip position to bowling shoulder. During the acceleration phase most of the lower trunk range of motion used by fast bowlers comes from contralateral side-flexion (Ranson et al., 2008). A study conducted by Perrett et al. (2020) investigated the association between spine lateral bending to BR speed variability and found no link between the two. However, in this study a link was found between VV_{BR} variability and Trunk-Z variability. Previous temporal analysis research of lower trunk range of motion found contralateral facet joint contact forces typically peaked during the start of the acceleration phase (Ranson et al., 2008). This trunk flexion posture also occurs at the time ground reaction forces are known to be high (Portus et al., 2004; Worthington et al., 2013b). Trunk effector variability could be influenced by these two occurring mechanisms, both acting as a coupling mechanism to influence effector variability at the same time. This may be a reason why lateral trunk flexion variability was not discovered as a compensatory coordinative factor in release parameter variability. However, it is not the only mechanism that may affect Trunk-Z variability, trunk range of motion also comes from upper trunk flexion.

Previous research has proposed that the amount of trunk flexion is a result of the bowling action mechanism (Worthington et al., 2013a). An optimised bowling action mechanism observes trunk flexion being influenced by front leg kinematics (Felton et al., 2020). When and where the upper trunk flexes occur will influence the variability of the acceleration phase. Analysis on a simulated optimised action by Felton et al. (2020) employed a technique where trunk flexion is delayed before flexing further than in matched simulation. This delay was likely linked to the transference of angular momentum through the front leg from horizontal and vertical loading rates (King et al., 2016). Front foot plant angle for instance had been correlated with horizontal and vertical loading rates (King et al., 2016). However, correlation analysis between upper trunk flexion and vertical loading rates had not been identified, which led King et al., (2016) to theorise there is no direct mechanical link between the two. A plausible delay in trunk flexion, though, may be result of changes in proximal and distal sequencing of the kinetic chain (Felton et al., 2020).

Proximal to distal sequencing of linear and rotational kinetic energy has been identified in cricket fast bowling (Ferdinands et al., 2013). It is probable the sequencing of proximal to distal kinetic energy is influential on Trunk-Z variability, as a delay in trunk flexion will mean the effector is remaining in an extended position for longer, before rapidly contracting and increasing variability through increased DoF. It is plausible that Trunk-Z and VV_{BR} variability may be influenced more so by energy transference through the torso than by a mechanical mechanism. However, further research would be needed to explore this topic. This study also found Trunk-Z variability had a negative contribution to vertical velocity control. This result means more variability in Trunk-Z is linked to reduced variability in VV_{BR}. It is plausible that VV_{BR} variability is likely a consequence of kinetic transference of energy and technique mechanics as these systems could allow active adjustment. This variability could be viewed as good variability in this effector system. Such would require further research with other data analysis tools and the possible use of the uncontrolled manifold theory to establish whether that variability is good.

12.4 Inter-effector cooperation of body posture

This section will explore the coordinated covariance of effector components in controlling whole-body effector variability.

The aim of study 4 was to investigate if whole-body effector position is relevant to the control task of fast bowling by analysing coordinated covariance between the effectors. The results from simulating random-like variability of elemental effector position on the collective whole-body effector position variability (S_WBEVleg, S_WBEVtrunk, S_WBEVarm) showed that the X-dimension and Z-dimension both had evidence of coordinated covariance between the elemental effectors. This means that the whole-body effector position in these two dimensions is relevant to the control system of a fast bowler. In contrast, the whole-body effector position in the Y-dimension showed no covariance, thus control of the whole-body effector position in the Y-dimension is somewhat irrelevant to the fast-bowler's task. In summary, these findings suggest an inter-effector cooperation to control the whole-body DoF in the XZ plane. Further research is needed to determine whether this is a deliberate strategy to mitigate goal-relevant variability by the fast bowler's control system, or whether this is simply an outcome of anatomical constraints inherent to the biomechanical details.

The finding that WBEV was significantly lower than the S_WBEV in the X-dimension supports evidence of inter-effector cooperation. This result was consistent across all three events (FFC, MID, BR) and for all three effector variability simulations (i.e., S_WBEV_{leg}, S_WBEV_{trunk}, S_WBEV_{arm}), whereby all were deemed significant ($p < .05$). Body position control in the X-dimension is likely to be associated with the need to control the collective goal of medio-lateral whole-body balance during the acceleration phase of the bowling action. However, further research is needed to determine the veracity of this link.

From theory of optimal feedback control, the cooperation between effector units is enabled because outgoing efferent motor commands (i.e., control of the DoF) will provide in advance the state estimate to the cooperating effectors (Diedrichsen et al., 2009). However, this state-dependent feedback mechanism is insufficient to signal the coordination of initial motor commands as each effector initially produces motor commands simultaneously in the motor movement (Diedrichsen et al., 2009). Thus, according to Diedrichsen et al. (2009), the theory explicitly assumes the existence of a common synergist command, whereby all effectors are synchronised at the same time to complete the movement. Conceptualising this theory with the motor task of a fast bowler, the three elemental effectors may need to be synchronised prior to the acceleration phase. However, as this study only analysed the acceleration phase, these prior initial conditions are, as yet, unknown. The transfer of kinetic energy has been shown to occur throughout the bowling action to assist in the generation of speed (Ferdinands et al., 2013) and it could be assumed that a similar mechanism may be important for directional and body posture control. Diedreichsen et al. (2009) has also stated that even unrelated movements, when initiated together, ultimately share in the same coupling and correlation of effector cooperation. However, at this stage it is yet to be fully determined whether the effectors are indeed cooperating together or acting independently. The findings of medio-lateral effector cooperation present a new avenue of research inquiry, which may lead to advancements in the understanding of posture control at BR and improvement in bowling performance objectives.

Aim 2 showed that Leg-X variability can explain some of the variability in VV_{BR} which, in-turn, was found to be critical to pitch length control (see Aim 2). In reference to the aim 4 investigation, Leg-X is part of a coordinated system to control WB-X. It could be theorised that Leg-X variability is utilised in both mechanisms and may be inter-related. Displacement between the front foot position and contra-lateral hip location during the acceleration phase could indicate that the stability of lower body position is important to the bowler; a similar principle has also been indicated in limb axis length in gait mechanics through proprioception coding, by adjusting limb length and orientation separately (Maioli and Poppele, 1991; Lacquanti and Maoili, 1994; Bosco et al., 1996; Ivanenko et al., 2007). Further analysis of intra-effector components (i.e., ankle inversion or eversion) could indicate anatomical constraints and/or cooperative mechanisms that influence the DoF of the leg displacement length in the X-dimension. Analysis methods, such as principal component analysis (Daffertshofer et al., 2004) and/or uncontrolled manifold theory (Scholz and Schöner, 1999) could be conducive to determining this influence of intra-effector control within the leg effector. With vertical velocity control being a critical factor for explaining pitch length control and Leg-X variability being linked to control of VV_{BR}; understanding the factors within the effector that adapt the medio-lateral limb length may shed new light on the leg effector X's role in bowling performance outcomes.

In the Z-dimension, S_WBEV-Z was found to be greater than WBEV-Z across the entirety of the acceleration phase, however only the S_WBEV_{leg}-Z was found to reach significance ($p < .05$). Therefore, the coordinated covariance results indicate that both Leg-X and Leg-Z contribute to mitigate WBEV-Z and WBEV-X, however control of WBEV-X is more meaningful. In contrast to the Trunk and Arm effectors, the Leg effector could be considered the most important (of the three effectors) for the control system. The importance for simultaneous Leg effector control in both X- and Z-dimensions is a new finding in fast bowling and has implications for coaching methods. It is difficult to provide context and support to these findings from other research studies because effector systems are not commonly explored in sports' biomechanics research. Only one study has demonstrated that leg effector control is possible in two dimensions, which was based on an analysis performed on gait (Ivanenko et al., 2007). Interestingly, despite Trunk-Z being found to influence BR vertical velocity control in aim 2, and $S\text{-}WBEV_{trunk}$ is larger than WBEV, inter-effector cooperation was not determined as being significant. However, as postulated previously in this thesis, Trunk-Z variability-inducing mechanisms such as contralateral trunk side-flexion (Ranson et al., 2008) may be impacted by other, ultimately perturbating influences, such as ground reaction forces, as they occur simultaneously (Portus et al., 2004; Worthington et al., 2013b). This may result in further destabilising effects, ultimately rendering any observed cooperation difficult to ascertain.

Unlike X- and Z-, the Y-dimension does not show the same level of coordinated covariance to reduce whole-body effector variability. Apart from the arm effector at the FFC event, neither the leg nor trunk effector simulations showed significant effect ($p < .05$) on whole-body variability. Interestingly, at BR all simulations of S_WBEV decreased compared to the WBEV. This indicates the bowlers, at that event, are producing an endpoint effector variability that is worse than a random outcome would likely be. At FFC, there might be a deliberate attempt by those effectors to disrupt coordinated covariance to enable whole-body effector position in the fore-aft (Y-) dimension to be more adaptable. Thus, it could be theorised that in this dimension, inter-effector cooperation and control of the Y-dimension is not relevant for control of fast bowling, but this is yet to be fully determined.

This investigation for the first time reported possible evidence of coordinated covariance of effectors, in controlling whole-body position at key events of the acceleration phase. Particularly, S_WBEV-X of each elemental effector (S_WBEV_{leg}, S_WBEV_{trunk}, S_WBEV_{arm}) showed significant results in coordinated covariance to control WBEV. This is an indication that in the X-dimension, for the successful completion of the bowling action, control of the collective goal of medio-lateral whole-body balance may be important. S_WBEV-Z also showed signs of coordinated covariance, especially S_WBEV_{leg}-Z which was found to be significant at BR. The finding of S_WBEV_{leg} in X- and Z-dimension at BR could be important to coaches, for understanding of how this variability in the leg and coordinated covariance may be beneficial to complete a successful bowling action.

13.0 Limitations

There are certain limitations for this study that are typical of such studies performed under laboratory conditions. Although an attempt was made to simulate match day conditions (i.e., bowlers bowled with a full match-day run-up), bowlers still bowled in an indoor testing environment in non-spiked athletic shoes and on synthetic surfaces, with equipment attached and researchers present, which may have presented a less-familiar environment. However, such testing gave greater opportunity for more detailed analysis of the fast-bowling action and has been previously used in the literature (Portus et al., 2000; Duffield et al., 2009; Callaghan et al., 2019). Synthetic surfaces may also have an impact on the bowlers' game length, as the ball's bounce could have been slightly different between this synthetic surface and other synthetic surfaces or match day pitches (Ball & Hrysomallis, 2012) and bowlers may have adjusted accordingly. As this study did not require the bowlers to hit a specific pitch target, rather a position upon passing or hitting the stumps, bowlers being in an unfamiliar environment and not on a game day turf pitch may have had to adjust their natural length in order to satisfy the top-of-off requirements of the researchers.

Different pitch bounce coefficients were not the only thing that may have affected the accuracy and pitch length control element of this study. Pitch length was determined by a flight predictor model based off constant acceleration and Vicon recorded BR parameter values. The equation utilised four release parameter inputs, ignoring other components such as drag, and spin coefficients, as used in other flight predictor models in cricket (Baker, 2010; Baker, 2013) and baseball pitching (Kusafuka et al., 2022). This would likely affect the ability of the model to accurately predict the length location. However, each delivery was assessed against a manually recorded pitch length observed by instructors on the recording day, and if it failed the inclusionary criteria it was removed from the analysis. The main purpose of the model was also to determine the effect of the four primary release parameters on pitch length control. This meant it was not used to specifically determine bowler accuracy, but to ascertain the most responsible release parameter. Kinematic variability was then assessed against the most prominent release parameter linked with determining pitch length control, bypassing any possible discrepancies in determining pitch length.

Another limitation of this study was the low number of participants utilised (n = 12), although they were similar and greater in number than the number utilised in other research analysing the effects of fast bowling technique and variability (Burnett et al., 1995; Callaghan et al., 2019), yet less than other cricket bowling studies (Ferdinands et al., 2013; Schaefer, et al., 2018). A smaller sample size can cause an issue by affecting the results a certain way when some bowlers have large differences in technique and performance capabilities to the normal group.

14.0 Implications

It has been previously identified that fast bowling accuracy was lacking in cricket fast bowling research (Glazier & Wheat, 2014). Accuracy of pitch position in cricket fast bowling may be determined in two dimensions, namely, length and width. This study focussed on investigating pitch length control and determining which BR parameters influenced pitch length variability. Vertical velocity control has been found here to be the primary influencing release parameter in determining pitch length variability. It was also discovered that there is little adaption of co-variability between parameters in controlling pitch length variability, as it appears that the on-line motor control adaptations required to compensate for any deviation in BR position, or BR horizontal velocity, cannot be achieved in the fast-bowling action. Therefore, improving reproducibility appears to be the bowler's best solution.

This study was further able to address an important gap in cricket fast bowling accuracy literature, as it was able to identify that the body position of effector components effects the control of the most critical BR parameter (VV_{BR}) for pitch length control. To date, no cricket fast bowling accuracy study had attempted to investigate this link. VV_{BR} variability was found to be significantly explained by two effector components, in Leg-X and Trunk-Z variability across the acceleration phase. Biomechanical patterns during this phase can explain these effector components and may shed new light on vertical velocity control. Leg-X variability was shown to positively influence VV_{BR} control. Therefore, coaching methods that improve the strength and stability of the front leg post FFC will likely be beneficial for fast bowlers in reducing their VV_{BR} and improving their pitch length control

Stability of Leg-X is also likely to be improved by stable bowling actions that avoid inconsistent movements, whereas Trunk-Z variability was negatively associated with VV_{BR} and, therefore, pitch length control. It is possible that more variability in this latter effector may even be beneficial to the overall task, as DoF allow the body many pathways through which it may move. Future coaching strategies may involve the promotion of new movement pathways within which fast bowlers may operate with greater DoF. However, this would be only enabled by a fast bowler's stable and solid base of the front leg after FFC.

To the knowledge of this author, analysis of the kinematic variability of the cricket fast bowling action is one of the more complex, high-speed movements in which this type of analysis has yet been performed. Although the understanding and study of simple movements in motor control are clearly important, more complex movements should also be explored (Morrison et al., 2016). Analysis undertaken in this study could broaden the understanding of kinematic variability and inter-effector cooperation in more complex motor tasks. Through the adoption of a new analysis method (Coordinated Covariance Test), this study was able to determine coordinated covariation of effector components in explaining whole-body posture. In the X-dimension, effector cooperation was found to be significant, indicating control of the medio-lateral whole-body position. This finding may be of importance to understand how the bowler is trying to control body posture at BR, by mitigating the effects of internal noise and perturbating forces. This new analysis method could be beneficial in determining inter-effector cooperation in other complex motor movements.

15.0 Future Directions

There are numerous future directions into which research could expand. Of the more major directions that have been somewhat highlighted by this thesis, vertical velocity control, as a component of accuracy, has received little attention in cricket fast bowling. As found in this study, vertical velocity control describes pitch length variability, however, analysis was only conducted on a good length. There is ample scope for further investigation of this influence on different set pitch lengths. There is also scope for investigation of the performance of bowlers of differing skill levels and genders in achieving pitch length control and vertical velocity control. As research has shown there are slight differences in accuracy performance achieved by differing skill levels (Phillips et al., 2012) and technique differences between males and females (Felton et al., 2019).

As also discovered in this study, Leg-X variability, along with Trunk-Z variability, is closely linked to vertical velocity control. This effector variability is composed of multiple intra-effector components (i.e., joint angles, segment lengths) which together represent the whole of the end-effector. The variability analysed in this study is the end-effector standard deviation of displacement throughout the acceleration phase. Therefore, the interaction of the intra-effector components has yet to be assessed. Adoption of other techniques, such as principal component analysis and/or uncontrolled manifold theory would be conducive to furthering understanding of intra-effector control mechanisms in cricket fast bowling.

Further, analysis of kinematic variability prior to FFC and the acceleration phase was not assessed in this study. However, there is possible evidence of coordination in the X-dimension prior to FFC as there was evidence of coordinated covariance at FFC, which could mean it was being controlled prior to that event. Understanding of kinematic variability and inter-effector cooperation in the BFC phase should relate to the acceleration phase and the possibility of a causal link between the latter two bowling phases should be investigated.

16.0 Conclusion

The purpose of this study was to investigate pitch length variability control mechanisms and kinematic variability in cricket fast bowling. This was achieved by investigating four aims.

The first aim investigated which of the four BR parameters could best explain pitch length variability (i.e., control). A multi-linear regression analysis found that the VV_{BR} was most responsible for determining pitch length variability. Further analysis of aim 1 was conducted to determine whether coordinated covariance was occurring between the four BR parameters in controlling pitch length variability. The coordinated covariance test identified limited coordinated co-variability amongst the release parameters. This indicated that the four release parameters vary in a random-like manner, where VV_{BR} had the largest independent impact on pitch length control. It appears that the on-line motor control adaptations required to compensate for any deviation in BR position, or BR horizontal velocity, cannot be achieved in the fast-bowling action. Therefore, improving reproducibility (mitigating variability) of the most sensitive parameter, VV_{BR}, appears to be the fast bowler's best solution to gaining pitch length control. The implication for future research suggests an enquiry on the influence of fine control of wrist and finger biomechanics on BR vertical velocity.

The second aim related to understanding the nature of kinematic variability across the acceleration phase. The findings supported the hypotheses that whole-body effector variability was more variable than the three elemental effectors and generally supported the hypothesis that effector variability did change throughout the acceleration phase. The results found that whole-body effector variability (WBEV), in the task-relevant X- and Z-dimensions, would reduce as the acceleration phase converges upon BR. The changes in variability and degree of variability found within the effector systems is ultimately an expression of a body's biomechanical states with an abundant system of many embodied DoF and a dynamical system affected by internal noise and external force perturbations.

The third aim investigated the influence of effector position variability on the most salient BR parameter, VV_{BR}. This aim addressed an important gap in the research literature by determining that body position has an effect on control of BR velocity which, in-turn, is critical to accurate bowling performance. Essentially, only two effector components, Leg-X and Trunk-Z, are required to explain most (R2 = .849) of the variability in VV_{BR} and influence the VVBR in different ways as Leg-X variability has a positive influence on VVBR variability, whilst Trunk-Z variability has a negative influence. Further research should investigate this preliminary, but important, finding. Both Leg-X and Trunk-Z can be explained by biomechanical patterns during the acceleration phase that will help derive critical features that could improve coaching methods and, therefore, performance outcomes in fast bowling accuracy.

The final aim investigated inter-effector cooperation to control whole-body effector variability (i.e., body posture control). From a coordinated covariate simulated shuffle analysis, the hypothesis that whole-body effector variability was controlled through inter-effector cooperation was investigated. The coordinated covariate test determined that hypothesis to be, at least, partially correct. In the X-dimension, effector cooperation was found to be significant for all simulated shuffled elemental effectors, indicating control of the medio-lateral whole-body posture. This cooperation was also observed in the Z-dimension, in particular S_WBEV_{leg} at FFC, which was found to be significant. The discovery of this possible cooperation occurring in Leg-X and -Z could be of importance to understand how the bowler is trying to control body posture at BR, by mitigating the effects of internal noise and perturbating forces. However, at FFC in the Y-dimension, S_WBEV showed no indication of coordinated covariance. It is plausible that there is an attempt to disrupt coordinated covariance to enable whole-body effector position in the fore-aft Y-dimension to be more adaptable and, therefore, coordinated covariance control of WBEV-Y may not be relevant for the task of fast bowling. However, further research should explore the effect of cooperation amongst the effectors in controlling whole-body effector variability and related performance outcomes.

Overall, this study has indicated control of VV_{BR} is necessary for performance and the control of pitch length. Results herein have identified, for the first time, that representing the body as functional effector components, shows promise to evaluate the phenomenon of motor variability that affects bowling control. The findings uncovered herein contribute new knowledge to the existing literature on pitch length control in cricket fast bowling; thus, leading to a useful platform to advance understanding of how a fast bowler's motor control system can structure variability in a bowling action to achieve optimal performance.

17.0 References

Antúnez, R. M., Hernández, F. J., García, J. P., Vaíllo, R. R., & Arroyo, J. S. (2012). Relationship between motor variability, accuracy, and ball speed in the tennis serve. *Journal of Human Kinetics*, *33*, 45-53. https://doi.org/10.2478/v10078-012-0043-3

Baker, C. J. (2010). A calculation of cricket ball trajectories. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, *224*(9), 1947-1958. https://doi.org/10.1243/09544062JMES1973

Baker, C. (2012). A unified framework for the prediction of cricket ball trajectories in spin and swing bowling. *Proceedings of the Institution of Mechanical Engineers, Part P:Journal of Sports Engineering and Technology*, *227*(1), 31-38. https://doi.org/10.1177/1754337112440793

Ball, K., & Hrysomallis, C. (2012). Synthetic grass cricket pitches and ball bounce characteristics. *Journal of Science and Medicine in Sport*, *15*(3), 272-276. https://doi.org/https://doi.org/10.1016/j.jsams.2011.10.010

Bartlett, R., Wheat, J., & Robins, M. (2007). Is movement variability important for sports biomechanists? *Sports Biomechanics*, *6*(2), 224-243. https://doi.org/10.1080/14763140701322994

Bayne, H., Elliott, B., Campbell, A., & Alderson, J. (2016). Lumbar load in adolescent fast bowlers: A prospective injury study. *Journal of Science and Medicine in Sport*, *19*(2), 117-122. https://doi.org/https://doi.org/10.1016/j.jsams.2015.02.011

Bernstein, N. A. (1967). *The co-ordination and regulation of movements.* Oxford, UK: Pergamon.

Bosco, G., Rankin, A., & Poppele, R. (1996). Representation of passive hindlimb postures in cat spinocerebellar activity. *Journal of Neurophysiology*, *76*(2), 715-726. https://doi.org/10.1152/jn.1996.76.2.715

Burnett, A. F., Elliott, B. C., & Marshall, R. N. (1995). The effect of a 12-over spell on fast bowling technique in cricket. *Journal of Sports Sciences*, *13*(4), 329-341. https://doi.org/10.1080/02640419508732247

Callaghan, S. J., Lockie, R. G., Andrews, W. A., Yu, W., Chipchase, R. F., & Nimphius, S. (2019). The effects of an eight over cricket bowling spell upon pace bowling biomechanics and performance within different delivery lengths. *Sports*, *7*(9), 200. https://www.mdpi.com/2075-4663/7/9/200

Callaghan, S. J., Lockie, R. G., Tallent, J., Chipchase, R. F., Andrews, W. A., & Nimphius, S. (2021). The effects of strength training upon front foot contact ground reaction forces and ball release speed among high-level cricket pace bowlers. *Sports Biomechanics*, 1-17. https://doi.org/10.1080/14763141.2021.1942540

Cazzola, D., Pavei, G., & Preatoni, E. (2016). Can coordination variability identify performance factors and skill level in competitive sport? The case of race walking. *Journal of Sport and Health Science, 5*(1), 35-43. https://doi.org/https://doi.org/10.1016/j.jshs.2015.11.005

Chen, H.-H., Liu, C., & Yang, W.-W. (2016). Coordination pattern of baseball pitching among young pitchers of various ages and velocity levels. *Journal of Sports Sciences, 34*(17), 1682-1690. https://doi.org/10.1080/02640414.2015.1133923

Chow, J. W., & Knudson, D. V. (2011). Use of deterministic models in sports and exercise biomechanics research. *Sports Biomechanics, 10*(3), 219-233. https://doi.org/10.1080/14763141.2011.592212

Cohen, R. G., & Sternad, D. (2009). Variability in motor learning: relocating, channeling and reducing noise. *Experimental Brain Research, 193*(1), 69-83. https://doi.org/10.1007/s00221-008-1596-1

Cohen, R. G., & Sternad, D. (2012). State space analysis of timing: exploiting task redundancy to reduce sensitivity to timing. *Journal of Neurophysiology, 107*(2), 618-627. https://doi.org/10.1152/jn.00568.2011

Cork, A., Justham, L., & West, A. (2013). Three-dimensional vision analysis to measure the release characteristics of elite bowlers in cricket. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology, 227*(2), 116-127. https://doi.org/10.1177/1754337112447264

Creswell, J. W., & Creswell, J. D. (2018). *Research design: qualitative, quantitative, and mixed methods approaches* (5th ed.). SAGE Publications.

Daffertshofer, A., Lamoth, C. J. C., Meijer, O. G., & Beek, P. J. (2004). PCA in studying coordination and variability: a tutorial. *Clinical Biomechanics, 19*(4), 415-428. https://doi.org/https://doi.org/10.1016/j.clinbiomech.2004.01.005

Devlin, L. H., Fraser, S. F., Barras, N. S., & Hawley, J. A. (2001). Moderate levels of hypohydration impairs bowling accuracy but not bowling velocity in skilled cricket players. *Journal of Science and Medicine in Sport, 4*(2), 179-187. https://doi.org/https://doi.org/10.1016/S1440-2440(01)80028-1

Diedrichsen, J., Shadmehr, R., & Ivry, R. B. (2010). The coordination of movement: optimal feedback control and beyond. *Trends in Cognitive Sciences, 14*(1), 31-39. https://doi.org/https://doi.org/10.1016/j.tics.2009.11.004

Duffield, R., Carney, M., & Karppinen, S. (2009). Physiological responses and bowling performance during repeated spells of medium-fast bowling. *Journal of Sports Sciences, 27*(1), 27-35. https://doi.org/10.1080/02640410802298243

Dupuy, M. A., Mottet, D., & Ripoll, H. (2000). The regulation of release parameters in underarm precision throwing. *Journal of Sports Sciences, 18*(6), 375-382. https://doi.org/10.1080/02640410050074304

Elliott, B. C. (2000). Back injuries and the fast bowler in cricket. *Journal of Sports Sciences, 18*(12), 983-991. https://doi.org/10.1080/026404100446784

Faisal, A. A., Selen, L. P., & Wolpert, D. M. (2008). Noise in the nervous system. *Nature reviews neuroscience, 9*(4), 292-303. https://doi.org/10.1038/nrn2258

Felton, P. J., Lister, S. L., Worthington, P. J., & King, M. A. (2019). Comparison of biomechanical characteristics between male and female elite fast bowlers. *Journal of Sports Sciences, 37*(6), 665-670. https://doi.org/10.1080/02640414.2018.1522700

Felton, P. J., Yeadon, M. R., & King, M. A. (2020). Optimising the front foot contact phase of the cricket fast bowling action. *Journal of Sports Sciences, 38*(18), 2054-2062. https://doi.org/10.1080/02640414.2020.1770407

Ferdinands, R. E. D., Kersting, U. G., & Marshall, R. N. (2013). Kinematic and kinetic energy analysis of segmental sequencing in cricket fast bowling. *Sports Technology, 6*(1), 10-21. https://doi.org/10.1080/19346182.2012.737800

Ferdinands, R. E. D., Kersting, U. G., & Marshall, R. N. (2014). A new taxonomic system for the sub classification of cricket bowling actions. *Sports Technology, 7*(1-2), 26-38. https://doi.org/10.1080/19346182.2014.893350

Ferdinands, R., Marshall, R. N., & Kersting, U. (2010). Centre of mass kinematics of fast bowling in cricket. *Sports Biomechanics, 9*(3), 139-152. https://doi.org/10.1080/14763141.2010.523844

Ferdinands, R. E. D., Sinclair, P. J., Stuelcken, M. C., & Greene, A. (2014). Rear leg kinematics and kinetics in cricket fast bowling. *Sports Technology, 7*(1-2), 52-61. https://doi.org/10.1080/19346182.2014.893352

Feros, S. A., Young, W. B., & O'Brien, B. J. (2018). Quantifying Cricket Fast Bowling Skill. *International Journal of Sports Physiology and Performance*, *13*(7), 830-838. https://doi.org/10.1123/ijspp.2017-0169

Fleisig, G., Chu, Y., Weber, A., & Andrews, J. (2009). Variability in baseball pitching biomechanics among various levels of competition. *Sports Biomechanics, 8*(1), 10-21. https://doi.org/10.1080/14763140802629958

Gelfand, I. M., & Latash, M. L. (1998). On the problem of adequate language in motor control. *Motor Control*, *2*(4), 306-313. https://doi.org/10.1123/mcj.2.4.306

Glanzer, J. A., Diffendaffer, A. Z., Slowik, J. S., Drogosz, M., Lo, N. J., & Fleisig, G. S. (2021). The relationship between variability in baseball pitching kinematics and consistency in pitch location. *Sports Biomechanics*, *20*(7), 879-886. https://doi.org/10.1080/14763141.2019.1642378

Glazier, P. S. (2010). Is the 'crunch factor' an important consideration in the aetiology of lumbar spine pathology in cricket fast bowlers? *Sports Medicine*, *40*(10), 809-815. https://doi.org/10.2165/11536590-000000000-00000

Glazier, P. (2011). Movement variability in the golf swing: Theoretical, methodological, and practical issues. *Research Quarterly for Exercise and Sport, 82*(2), 157-161. https://doi.org/10.1080/02701367.2011.10599742

Glazier, P. S., Paradisis, G. P., & Cooper, S. M. (2000). Anthropometric and kinematic influences on release speed in men's fast-medium bowling. *Journal of Sports Sciences, 18*(12), 1013-1021. https://doi.org/10.1080/026404100446810

Glazier, P. S., & Wheat, J. S. (2014). An integrated approach to the biomechanics and motor control of cricket fast bowling techniques. *Sports Medicine*, *44*(1), 25-36. https://doi.org/10.1007/s40279-013-0098-x

Glazier, P. S., & Worthington, P. J. (2014). The impact of centre of mass kinematics and ground reaction forces on ball release speeds in cricket fast bowling. *Sports Technology*, *7*(1-2), 4-11. https://doi.org/10.1080/19346182.2014.893351

Guimarães, A. N., Ugrinowitsch, H., Dascal, J. B., Porto, A. B., & Okazaki, V. H. A. (2020) Freezing degrees of freedom during motor learning: A systematic review. *Motor Control*, *24*(3), 457-471. https://doi.org/10.1123/mc.2019-0060

Harris, C. M., & Wolpert, D. M. (1998). Signal-dependent noise determines motor planning. *Nature, 394*(6695), 780-784. https://doi.org/10.1038/29528

Harwood, M. J., Yeadon, M. R., & King, M. A. (2018). Does shortening the pitch make junior cricketers bowl better? *Journal of Sports Sciences, 36*(17), 1972-1978. https://doi.org/10.1080/02640414.2018.1428884

Harwood, M. J., Yeadon, M. R., & King, M. A. (2019). A shorter cricket pitch improves decision making by junior batters. *Journal of Sports Sciences, 37*(17), 1934-1941. https://doi.org/10.1080/02640414.2019.1606760

Ivanenko, Y. P., Cappellini, G., Dominici, N., Poppele, R. E., & Lacquaniti, F. (2005). Coordination of locomotion with voluntary movements in humans. *The Journal of Neuroscience, 25*(31), 7238-7253. https://doi.org/10.1523/jneurosci.1327-05.2005

Ivanenko, Y. P., Cappellini, G., Dominici, N., Poppele, R. E., & Lacquaniti, F. (2007). Modular control of limb movements during human locomotion. *The Journal of Neuroscience, 27*(41), 11149-11161. https://doi.org/10.1523/jneurosci.2644-07.2007

Kawamura, K., Shinya, M., Kobayashi, H., Obata, H., Kuwata, M., & Nakazawa, K. (2017). Baseball pitching accuracy: an examination of various parameters when evaluating pitch locations. *Sports Biomechanics*, *16*(3), 399-410. https://doi.org/10.1080/14763141.2017.1332236

King, M. A., Worthington, P. J., & Ranson, C. A. (2016). Does maximising ball speed in cricket fast bowling necessitate higher ground reaction forces? *Journal of Sports Sciences*, *34*(8), 707-712. https://doi.org/10.1080/02640414.2015.1069375

Kobayashi, Y., Ae, M., Miyazaki, A., Fujii, N., Iiboshi, A., & Nakatani, H. (2016). Kinetics of throwing arm joints and the trunk motion during an overarm distance throw by skilled Japanese elementary school boys. *Sports Biomechanics*, *15*(3), 314-328. https://doi.org/10.1080/14763141.2016.1161820

Kudo, K., Tsutsui, S., Ishikura, T., Ito, T., & Yamamoto, Y. (2000). Compensatory coordination of release parameters in a throwing task. *Journal of Motor Behavior, 32*(4), 337-345. https://doi.org/10.1080/00222890009601384

Kusafuka, A., Kobayashi, H., Miki, T., Kuwata, M., Kudo, K., Nakazawa, K., & Wakao, S. (2020). Influence of release parameters on pitch location in skilled baseball pitching. *Frontiers in Sports and Active Living*, *2*(36), 1-9. https://doi.org/10.3389/fspor.2020.00036

Kusafuka, A., Kudo, K., & Nakazawa, K. (2022). Control of accuracy during movements of high speed: Implications from baseball pitching. *Journal of Motor Behavior*, *54*(3), 304-315. https://doi.org/10.1080/00222895.2021.1960789

Lacquaniti, F., Guigon, E., Bianchi, L., Ferraina, S., & Caminiti, R. (1995). Representing spatial information for limb movement: Role of area 5 in the monkey. *Cerebral Cortex, 5*(5), 391-409. https://doi.org/10.1093/cercor/5.5.391

Lacquaniti, F., & Maioli, C. (1994). Coordinate transformations in the control of cat posture. *Journal of Neurophysiology, 72*(4), 1496-1515. https://doi.org/10.1152/jn.1994.72.4.1496

Latash, M. L. (2012). The bliss (not the problem) of motor abundance (not redundancy). *Experimental Brain Research, 217*(1), 1-5. https://doi.org/10.1007/s00221-012-3000-4

Latash, M. L. (2018). Abundant degrees of freedom are not a problem. *Kinesiology Review, 7*(1), 64-72. https://doi.org/10.1123/kr.2017-0058

Lindsay, C., & Spratford, W. (2020). Bowling action and ball flight kinematics ofconventional swing bowling in pathway and high-performance bowlers. *Journal of Sports Sciences, 38*(14), 1650-1659. https://doi.org/10.1080/02640414.2020.1754717

Maioli, C., & Poppele, R. E. (1991). Parallel processing of multisensory information concerning self motion. *Experimental Brain Research, 87*(1), 119-125. https://doi.org/10.1007/BF00228513

Marshall, R. N., & Elliott, B. C. (2000). Long-axis rotation: The missing link in proximal to-distal segmental sequencing. *Journal of Sports Sciences, 18*(4), 247-254. https://doi.org/10.1080/026404100364983

McDonald, P. V., van Emmerik, R. E. A., & Newell, K. M. (1989). The effects ofpractice on limb kinematics in a throwing task. *Journal of Motor Behavior, 21*(3), 245-264. https://doi.org/10.1080/00222895.1989.10735480

McGrath, J. W., Neville, J., Stewart, T., Lamb, M., Alway, P., King, M., & Cronin, J. (2022). The relationship between bowling intensity and ground reaction force in cricket pace bowlers. *Journal of Sports Sciences*, 1-7. https://doi.org/10.1080/02640414.2022.2094561

McNamara, D. J., Gabbett, T. J., Chapman, P., Naughton, G., & Farhart, P. (2015). Variability of PlayerLoad, bowling velocity, and performance execution in fast bowlers across repeated bowling spells. *International Journal of Sports Physiology and Performance*, *10*(8), 1009-1014. https://doi.org/10.1123/ijspp.2014-0497

Mehdizadeh, S., & Glazier, P. S. (2021). Effect of simulated sensorimotor noise on kinematic variability and stability of a biped walking model. *Computer Methods in Biomechanics and Biomedical Engineering, 24*(10), 1097-1103. https://doi.org/10.1080/10255842.2020.1867852

Middleton, K. J., Mills, P. M., Elliott, B. C., & Alderson, J. A. (2016). The association between lower limb biomechanics and ball release speed in cricket fast bowlers: a comparison of high performance and amateur competitors. *Sports Biomechanics*, *15*(3), 357-369. https://doi.org/10.1080/14763141.2016.1163413

Morrison, A., McGrath, D., & Wallace, E. S. (2016). Motor abundance and control structure in the golf swing. *Human Movement Science*, *46*, 129-147. https://doi.org/https://doi.org/10.1016/j.humov.2016.01.009

Loosch, H. M. E., & Müller, H. (1999). Functional variability and an equifinal path of movement during targeted throwing. *Journal 01 Human Movement Studies*, *36*, 103-126.

Nabavinik, M., & Abdolzadeh, H. (2020). Moderate movement variability is optimal in massive - practiced dart throws. *Pedagogy of Physical Culture and Sports*, *24*(6), 297-302. https://doi.org/10.15561/26649837.2020.0604

Nakano, N., Iino, Y., Inaba, Y., Fukashiro, S., & Yoshioka, S. (2022). Utilizing hierarchical redundancy for accurate throwing movement. *Human Movement Science*, *81*, 1-10. https://doi.org/https://doi.org/10.1016/j.humov.2021.102918

Nagami, T., Morohoshi, J., Higuchi, T., Nakata, H., Naito, S., & Kanosue, K. (2011). Spin on fastballs thrown by elite baseball pitchers. *Medicine & Science in Sports & Exercise*, *43*(12), 2321-2327. https://doi.org/10.1249/MSS.0b013e318220e728

Nasu, D., Matsuo, T., & Kadota, K. (2014). Two types of motor strategy for accurate dart throwing. *PLoS ONE*, *9*(2), 1–9. https://doi.org/10.1371/journal.pone.0088536

Olivier, B., Taljaard, T., Burger, E., Brukner, P., Orchard, J., Gray, J., Botha, N., Stewart, A., & McKinon, W. (2016). Which extrinsic and intrinsic factors are associated with non-contact injuries in adult cricket fast bowlers? *Sports Medicine*, *46*(1), 79-101. https://doi.org/10.1007/s40279-015-0383-y

Peploe, C., McErlain-Naylor, S. A., Harland, A. R., Yeadon, M. R., & King, M. A. (2018). A curve fitting methodology to determine impact location, timing, and instantaneous post-impact ball velocity in cricket batting. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*, *232*(3), 185-196. https://doi.org/10.1177/1754337117723275

Perrett, C., Bussey, M. D., & Lamb, P. F. (2020). Movement variability in the spinal kinematics of fast bowlers. *ISBS Proceedings Archive 38*(1), (pp. 284-287).

Phillips, E., Portus, M., Davids, K., & Renshaw, I. (2012). Performance accuracy and functional variability in elite and developing fast bowlers. *Journal of Science and Medicine in Sport*, *15*(2), 182-188. https://doi.org/https://doi.org/10.1016/j.jsams.2011.07.006

Portus, M. R., Mason, B. R., Elliott, B. C., Pfitzner, M. C., & Done, R. P. (2004). Technique factors related to ball release speed and trunk injuries in high performance cricket fast bowlers. *Sports Biomechanics*, *3*(2), 263-284. https://doi.org/10.1080/14763140408522845

Portus, M. R., Sinclair, P. J., Burke, S. T., Moore, D. J. A., & Farhart, P. J. (2000). Cricket fast bowling performance and technique and the influence of selected physical factorsduring an 8 over spell. *Journal of Sports Sciences*, *18*(12), 999-1011. https://doi.org/10.1080/026404100446801

Ranson, C. A., Burnett, A. F., King, M., Patel, N., & O'Sullivan, P. B. (2008). The relationship between bowling action classification and three-dimensional lower trunk motion in fast bowlers in cricket. *Journal of Sports Sciences*, *26*(3), 267-276. https://doi.org/10.1080/02640410701501671

Roitman, A. V., Pasalar, S., Johnson, M. T. V., & Ebner, T. J. (2005). Position, direction of movement, and speed tuning of cerebellar Purkinje cells during circular manual tracking in monkey. *The Journal of Neuroscience*, *25*(40), 9244-9257. https://doi.org/10.1523/jneurosci.1886-05.2005

Rosenblatt, N. J., Hurt, C. P., Latash, M. L., & Grabiner, M. D. (2014). An apparent contradiction: increasing variability to achieve greater precision? *Experimental Brain Research*, *232*(2), 403-413.https://doi.org/10.1007/s00221-013-3748-1

Salter, C. W., Sinclair, P. J., & Portus, M. R. (2007). The associations between fast bowling technique and ball release speed: A pilot study of the within-bowler and between bowler approaches. *Journal of Sports Sciences*, *25*(11), 1279-1285. https://doi.org/10.1080/02640410601096822

Sarpeshkar, V., Mann, D. L., Spratford, W., & Abernethy, B. (2017). The influence of ball-swing on the timing and coordination of a natural interceptive task. *Human Movement Science*, *54*, 82-100. https://doi.org/https://doi.org/10.1016/j.humov.2017.04.003

Sayyah, M., King, M. A., Hiley, M. J., & Yeadon, M. R. (2020). Functional variability in the takeoff phase of one metre springboard forward dives. *Human Movement Science*, *72*, 102634. https://doi.org/https://doi.org/10.1016/j.humov.2020.102634

Scarborough, D. M., Bassett, A. J., Mayer, L. W., & Berkson, E. M. (2020). Kinematic sequence patterns in the overhead baseball pitch. *Sports Biomechanics*, *19*(5), 569-586. https://doi.org/10.1080/14763141.2018.1503321

Schaefer, A., O'Dwyer, N., Ferdinands, R. E. D., & Edwards, S. (2018). Consistency of kinematic and kinetic patterns during a prolonged spell of cricket fast bowling: an exploratory laboratory study. *Journal of Sports Sciences*, *36*(6), 679-690. https://doi.org/10.1080/02640414.2017.1330548

Scholz, J. P., & Schöner, G. (1999). The uncontrolled manifold concept: identifying control variables for a functional task. *Experimental Brain Research*, *126*(3), 289-306. https://doi.org/10.1007/s002210050738

Schwartz, A. B., & Moran, D. W. (2000). Arm trajectory and representation of movement processing in motor cortical activity. *European Journal of Neuroscience*, *12*(6), 1851-1856. https://doi.org/https://doi.org/10.1046/j.1460-9568.2000.00097.x

Schwartz, M. H., & Rozumalski, A. (2005). A new method for estimating joint parameters from motion data. *Journal of Biomechanics*, *38*(1), 107-116. https://doi.org/https://doi.org/10.1016/j.jbiomech.2004.03.009

Shafizadeh, M., Bonner, S., Barnes, A., & Fraser, J. (2020). Effects of task and environmental constraints on axial kinematic synergies during the tennis service in expert players. *European Journal of Sport Science*, *20*(9), 1178-1186. https://doi.org/10.1080/17461391.2019.1701093

Shafizadeh, M., Bonner, S., Fraser, J., & Barnes, A. (2019). Effect of environmental constraints on multi-segment coordination patterns during the tennis service in expert performers. *Journal of Sports Sciences*, *37*(9), 1011-1020. https://doi.org/10.1080/02640414.2018.1538691

Solomito, M. J., Cohen, A. D., & Garibay, E. J. (2020). Influence of stride length on upper extremity joint moments and ball velocity in collegiate baseball pitchers. *Sports Biomechanics*, 1-10. https://doi.org/10.1080/14763141.2020.1809698

Taliep, M., Gray, J., Gibson, A., Calder, S., Lambert, M., & Noakes, T. (2003). The effects of a 12-over bowling spell on bowling accuracy and pace in cricket fast bowlers. *Journal of Human Movement Studies*, *45*(3), 197-217.

Van Emmerik, R. E. A., Ducharme, S. W., Amado, A. C., & Hamill, J. (2016). Comparing dynamical systems concepts and techniques for biomechanical analysis. *Journal of Sport and Health Science*, *5*(1), 3-13. https://doi.org/https://doi.org/10.1016/j.jshs.2016.01.013

Van Emmerik, R. E. A., Hamill, J., & McDermott, W. J. (2005). Variability and coordinative function in human gait. *Quest*, *57*(1), 102-123. https://doi.org/10.1080/00336297.2005.10491845

Wagner, H., Pfusterschmied, J., Klous, M., von Duvillard, S. P., & Müller, E. (2012). Movement variability and skill level of various throwing techniques. *Human Movement Science*, *31*(1), 78-90. https://doi.org/https://doi.org/10.1016/j.humov.2011.05.005

Winter, D. A. (1990). *Biomechanics and motor control of human movement*. Willey.

Witte, K., Ganter, N., Baumgart, C., & Peham, C. (2010). Applying a principal component analysis to movement coordination in sport. *Mathematical and Computer Modelling of Dynamical Systems, 16*(5), 477-488. https://doi.org/10.1080/13873954.2010.507079

Wormgoor, S., Harden, L., & McKinon, W. (2010). Anthropometric, biomechanical, and isokinetic strength predictors of ball release speed in high-performance cricket fast bowlers. *Journal of Sports Sciences*, *28*(9), 957-965. https://doi.org/10.1080/02640411003774537

Worthington, P. J., King, M. A., & Ranson, C. A. (2013a). Relationships between fast bowling technique and ball release speed in cricket. *Journal of Applied Biomechanics*, *29*(1), 78-84. https://doi.org/10.1123/jab.29.1.78

Worthington, P., King, M., & Ranson, C. (2013b). The influence of cricket fast bowlers' front leg technique on peak ground reaction forces. *Journal of Sports Sciences*, *31*(4),434-441. https://doi.org/10.1080/02640414.2012.736628

Wu, Y. H., & Latash, M. L. (2014). The effects of practice on coordination. *Exercise Sport Science Review*, *42*(1), 37-42. https://doi.org/10.1249/jes.0000000000000002

Yang, J. F., & Scholz, J. P. (2005). Learning a throwing task is associated with differential changes in the use of motor abundance. *Experimental Brain Research*, *163*(2), 137-158. https://doi.org/10.1007/s00221-004-2149-x

Yang, J. F., Scholz, J. P., & Latash, M. L. (2007). The role of kinematic redundancy in adaptation of reaching. *Experimental Brain Research*, *176*(1), 54-69. https://doi.org/10.1007/s00221-006-0602-8

18.0 Appendices

18.1 Release parameter variables

Table 18.1.1: *Bowler and group release parameter variables mean and standard deviation.*

Bowler	Horizontal Release Position (% Ht)	Vertical Release Position (% Ht)	Ball Release Angle (θ)	Stride Length (% Ht)	BFC to FFC Time (s)	FFC to BR Time (s)
1	0.28 ± 0.02	1.01 ± 0.01	-6.38 ± 1.54	0.81 ± 0.02	0.17 ± 0.01	0.11 ± 0.00
2	0.39 ± 0.03	1.10 ± 0.01	-7.42 ± 1.67	0.90 ± 0.02	0.23 ± 0.00	0.10 ± 0.01
3	0.23 ± 0.05	1.13 ± 0.01	-6.03 ± 1.68	0.85 ± 0.03	0.23 ± 0.01	0.10 ± 0.01
4	0.38 ± 0.04	1.13 ± 0.02	-8.79 ± 2.31	0.80 ± 0.02	0.23 ± 0.02	0.12 ± 0.01
5	0.28 ± 0.04	1.09 ± 0.01	-6.28 ± 1.80	0.79 ± 0.02	0.15 ± 0.01	0.11 ± 0.00
6	0.27 ± 0.05	1.12 ± 0.01	-4.61 ± 1.54	0.79 ± 0.03	0.18 ± 0.01	0.11 ± 0.01
7	0.37 ± 0.02	1.04 ± 0.01	-6.16 ± 2.10	0.90 ± 0.02	0.21 ± 0.01	0.10 ± 0.00
8	0.41 ± 0.04	1.10 ± 0.01	-6.27 ± 1.88	0.86 ± 0.02	0.21 ± 0.01	0.11 ± 0.00
9	0.00 ± 0.02	1.09 ± 0.01	-6.83 ± 2.14	0.80 ± 0.01	0.20 ± 0.01	0.11 ± 0.01
10	0.31 ± 0.04	1.11 ± 0.01	-7.03 ± 2.17	0.92 ± 0.03	0.22 ± 0.01	0.11 ± 0.00
11	0.35 ± 0.02	1.18 ± 0.01	-5.15 ± 2.44	0.82 ± 0.04	0.24 ± 0.01	0.11 ± 0.00
12	0.49 ± 0.03	1.16 ± 0.01	-7.08 ± 2.43	0.91 ± 0.03	0.20 ± 0.01	0.12 ± 0.00
Group	0.31 ± 0.03	1.10 ± 0.01	-6.50 ± 1.97	0.85 ± 0.02	0.21 ± 0.01	0.11 ± 0.01

18.2 Mean absolute vertical velocity error to pitch length variability correlations

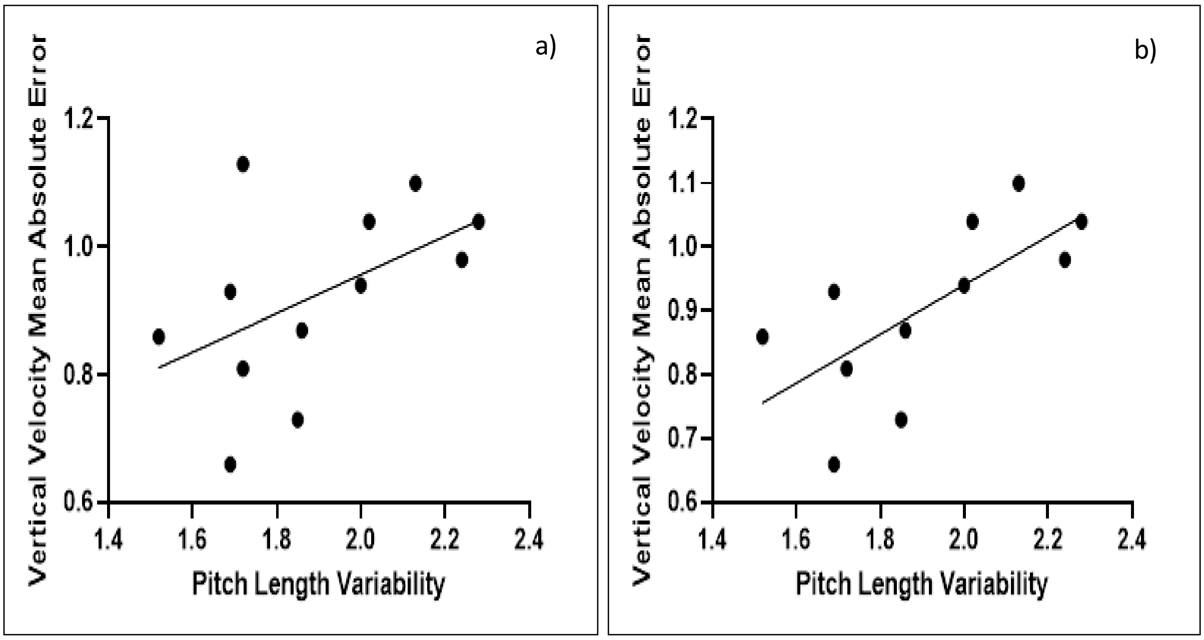

Figure 18.2.1: *a) Vertical velocity mean absolute error to pitch length variability correlation plot. Includes all bowlers. b) Vertical velocity mean absolute error to pitch length variability correlation plot. Includes all bowlers except bowler 4. Grubbs' test found bowler 4 did not satisfy excluding from the correlation plot.*

Figure 18.2.1a correlation plot between vertical velocity error standard deviation and performed vertical velocity standard deviation amongst the whole bowling cohort indicated an insignificant, weak correlation (R = .502, R^2 = .252, p = .960). When a Grubbs' test was performed to test if there were any outliers in the data there was no indication of there being an outlier. However, if bowler 4 was removed from the correlation, because bowler 4 had a shorter than normal mean pitch length of 8.29 m compared to the group mean of 6.12 m, it produced a strong correlation (R = .693, R^2 = .480, p = .018) (Figure 18.2.1b).

18.3 Elemental effector waveforms

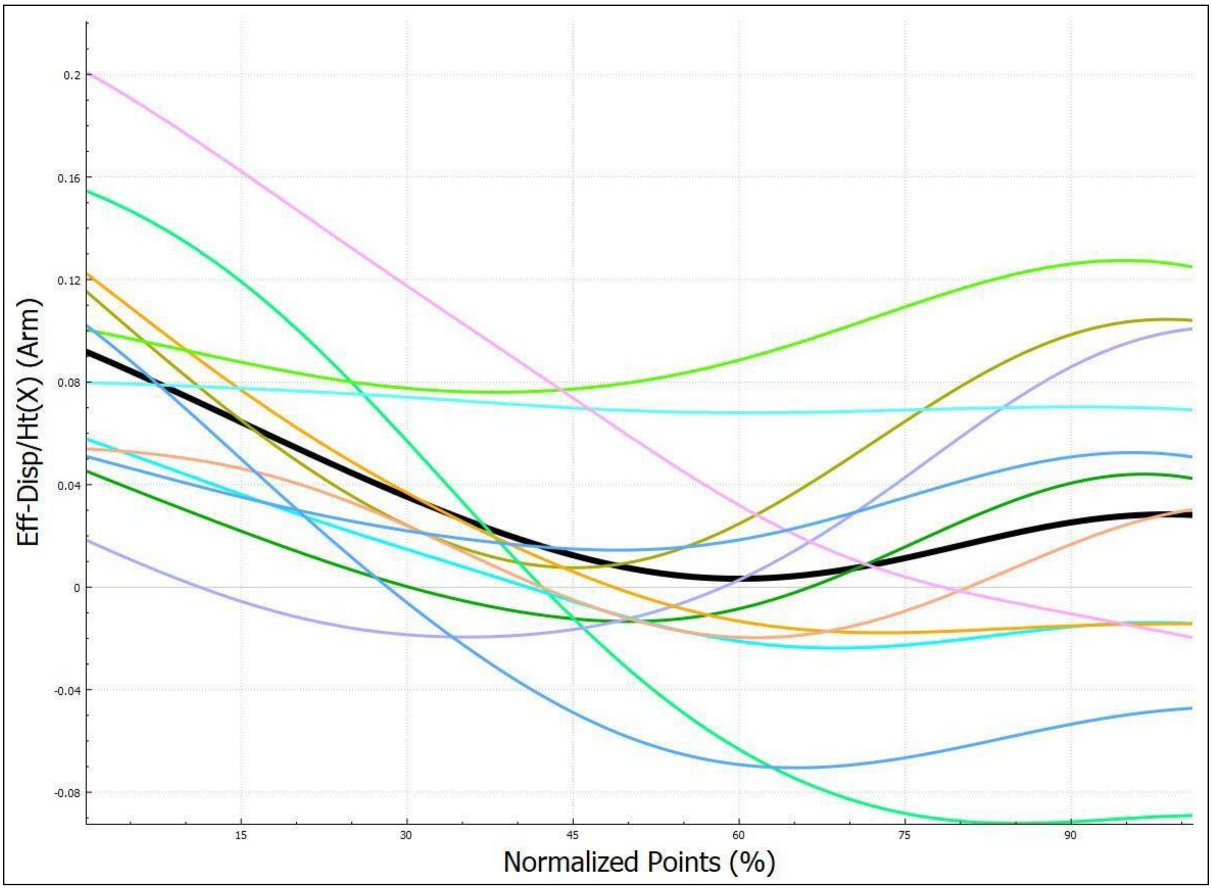

Figure 18.3.1*: Signal graph of the Arm effector displacement waveforms in the X-dimension across the acceleration phase. Individual bowler's mean waveforms are represented by each colour with the group mean waveform represented by the bold black line.*

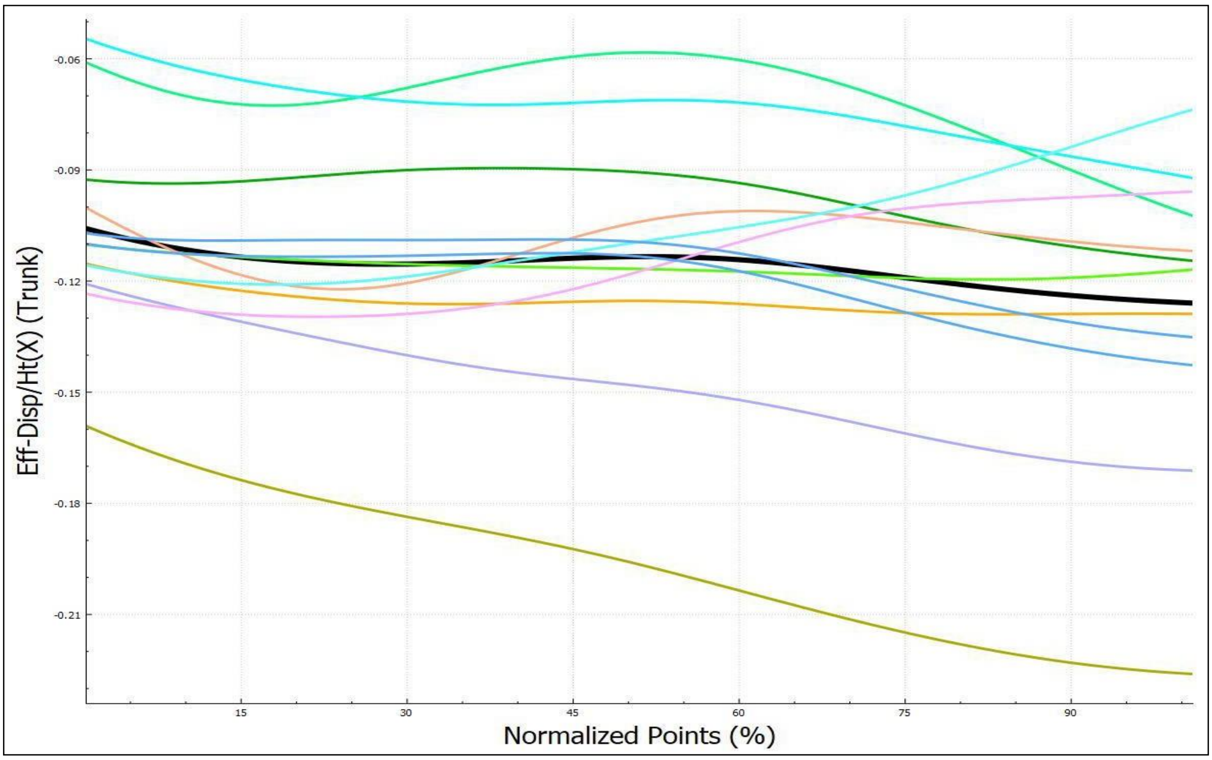

Figure 18.3.2: *Signal graph of the Trunk effector displacement waveforms in the X-dimension across the acceleration phase. Individual bowler's mean waveforms are represented by each colour with the group mean waveform represented by the bold black line.*

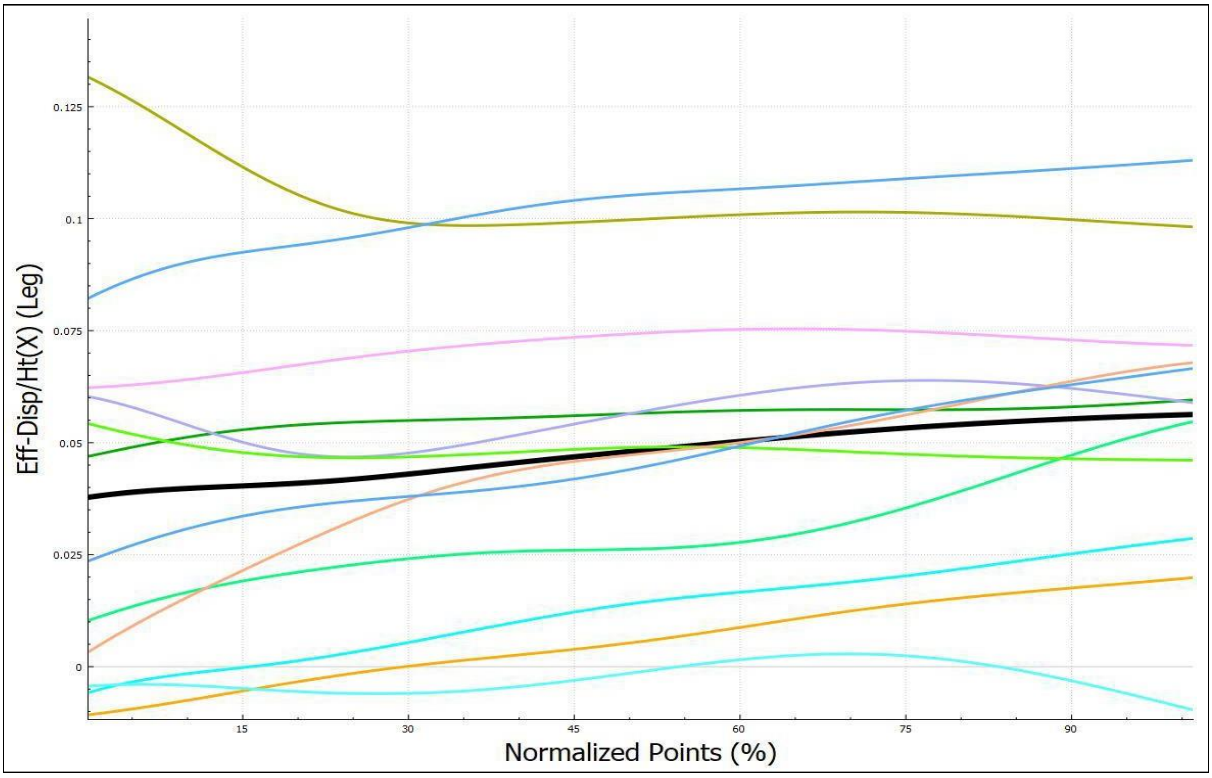

Figure 18.3.3: *Signal graph of the Leg effector displacement waveforms in the X-dimension across the acceleration phase. Individual bowler's mean waveforms are represented by each colour with the group mean waveform represented by the bold black line.*

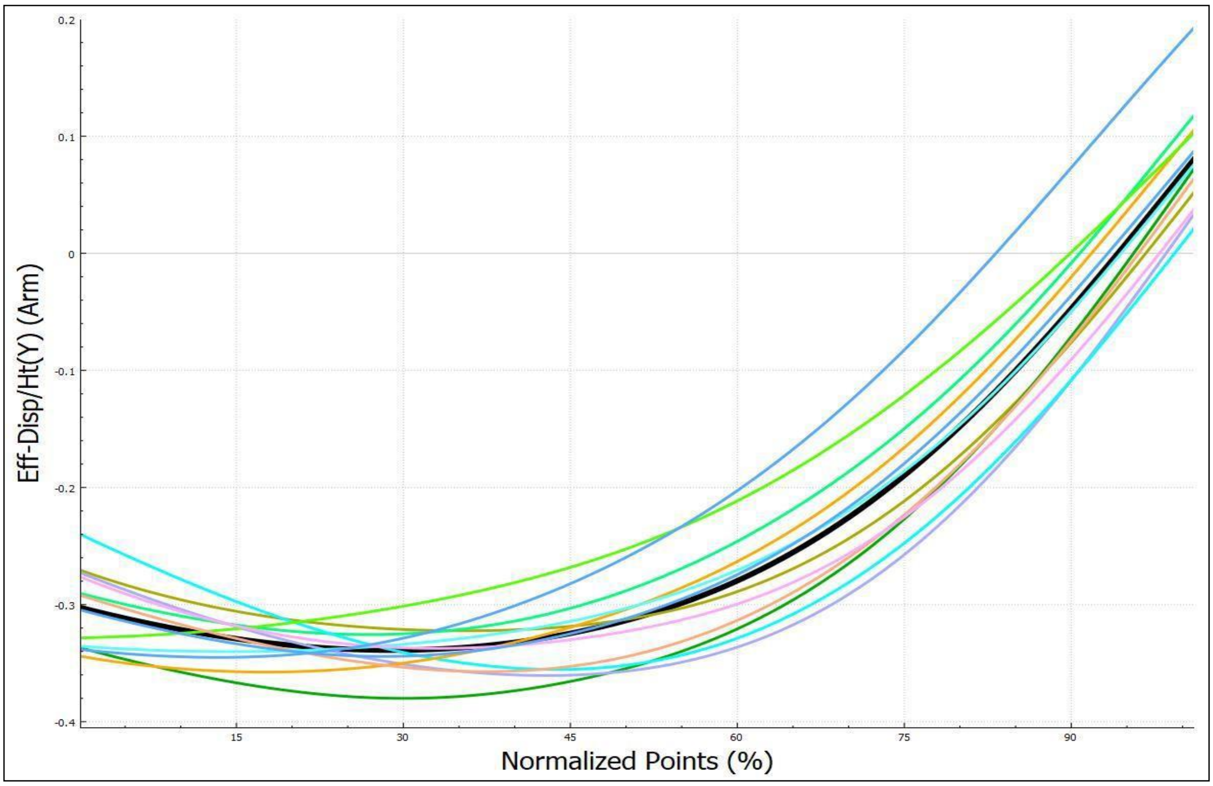

Figure 18.3.4: *Signal graph of the Arm effector displacement waveforms in the Y-dimension across the acceleration phase. Individual bowler's mean waveforms are represented by each colour with the group mean waveform represented by the bold black line.*

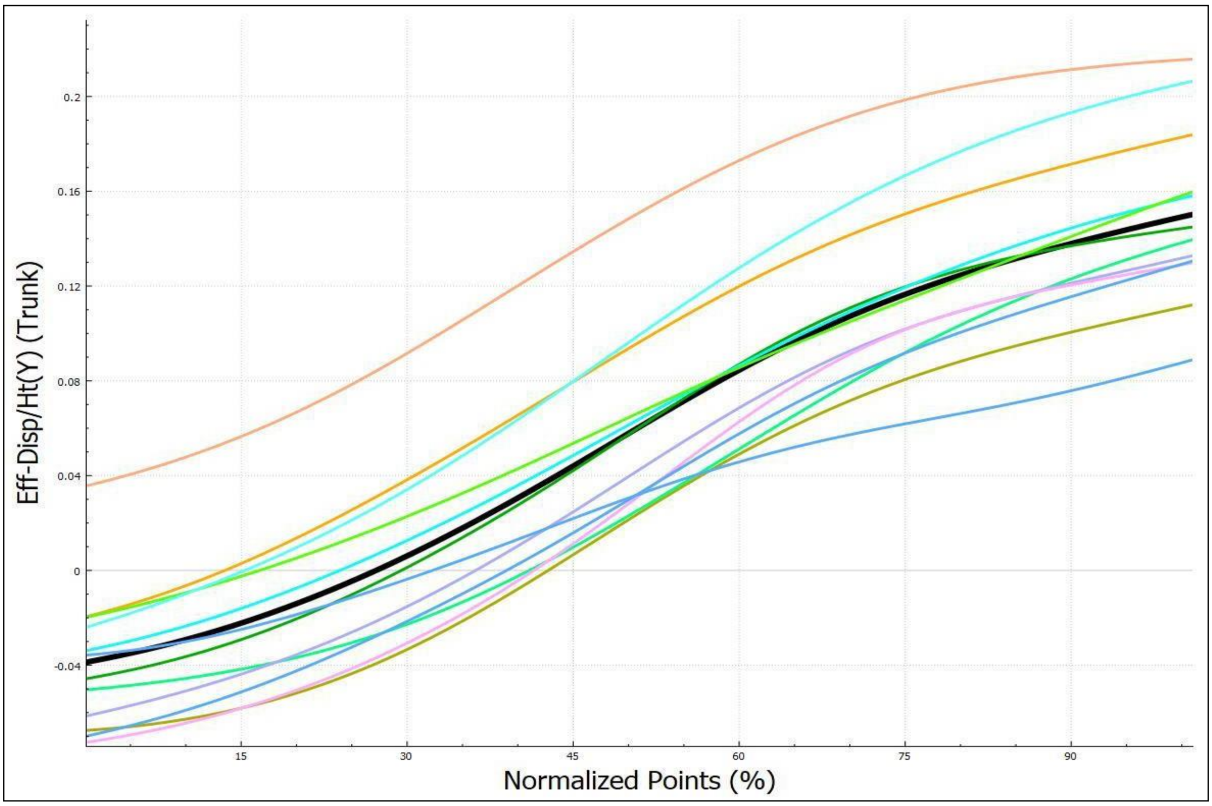

Figure 18.3.5: *Signal graph of the Trunk effector displacement waveforms in the Y-dimension across the acceleration phase. Individual bowler's mean waveforms are represented by each colour with the group mean waveform represented by the bold black line.*

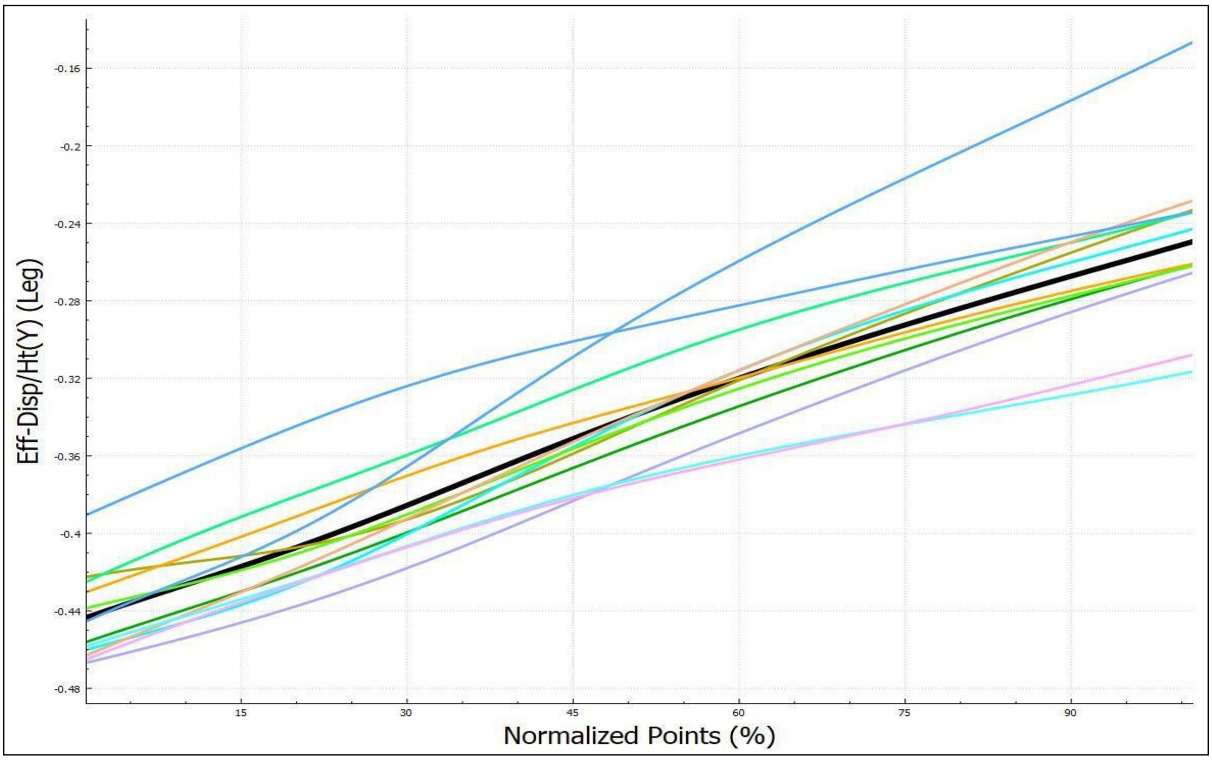

Figure 18.3.6: *Signal graph of the Leg effector displacement waveforms in the Y-dimension across the acceleration phase. Individual bowler's mean waveforms are represented by each colour with the group mean waveform represented by the bold black line.*

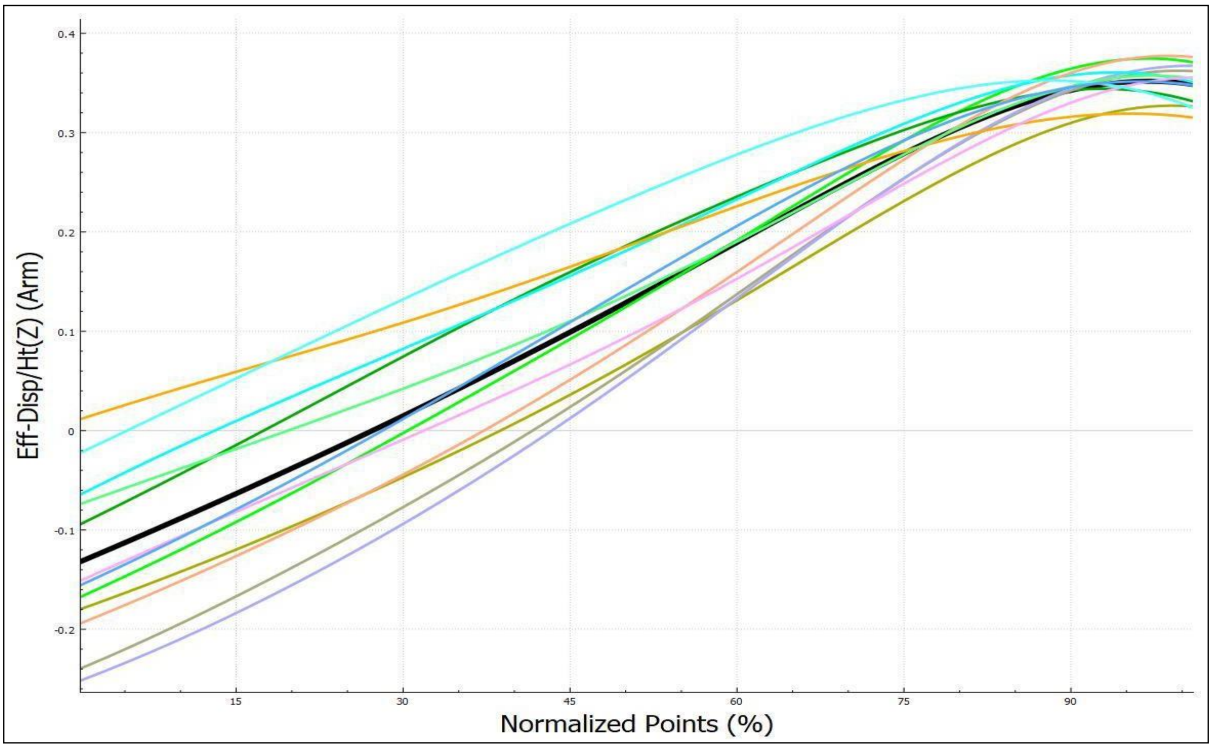

Figure 18.3.7: *Signal graph of the Arm effector displacement waveforms in the Z-dimension across the acceleration phase. Individual bowler's mean waveforms are represented by each colour with the group mean waveform represented by the bold black line.*

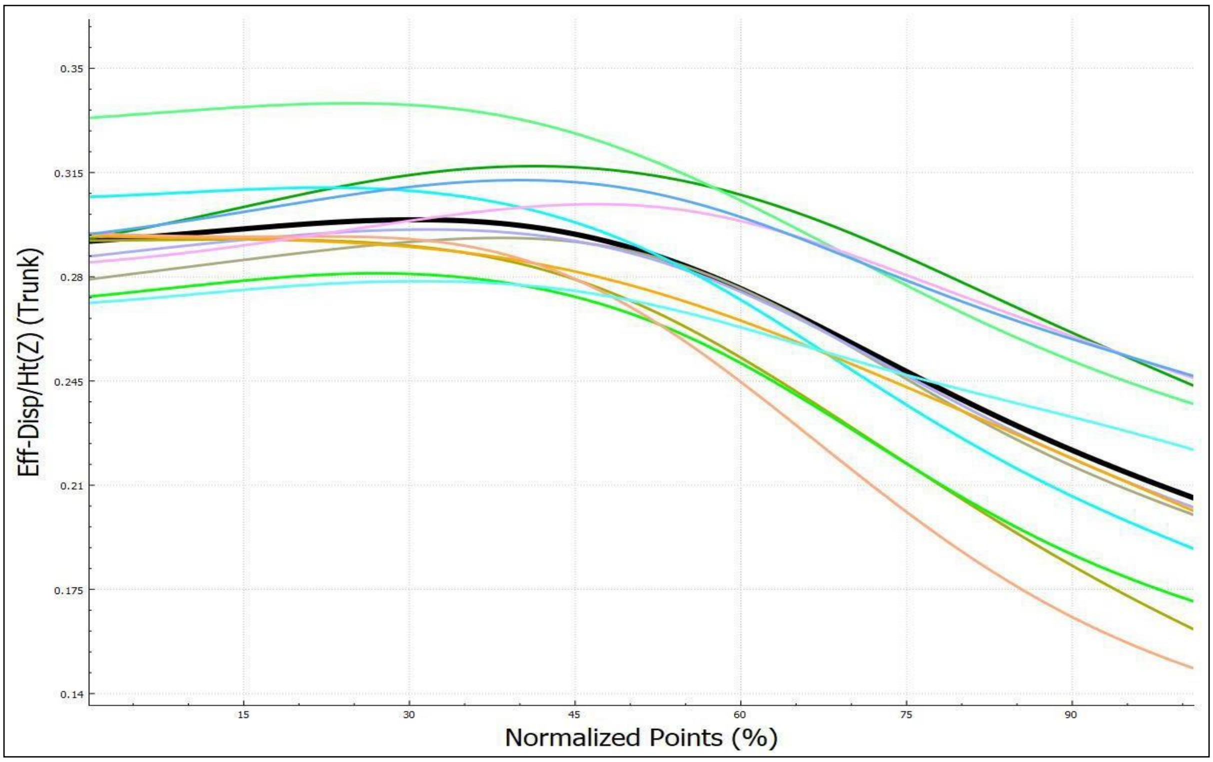

Figure 18.3.8: *Signal graph of the Trunk effector displacement waveforms in the Z-dimension across the acceleration phase. Individual bowler's mean waveforms are represented by each colour with the group mean waveform represented by the bold black line.*

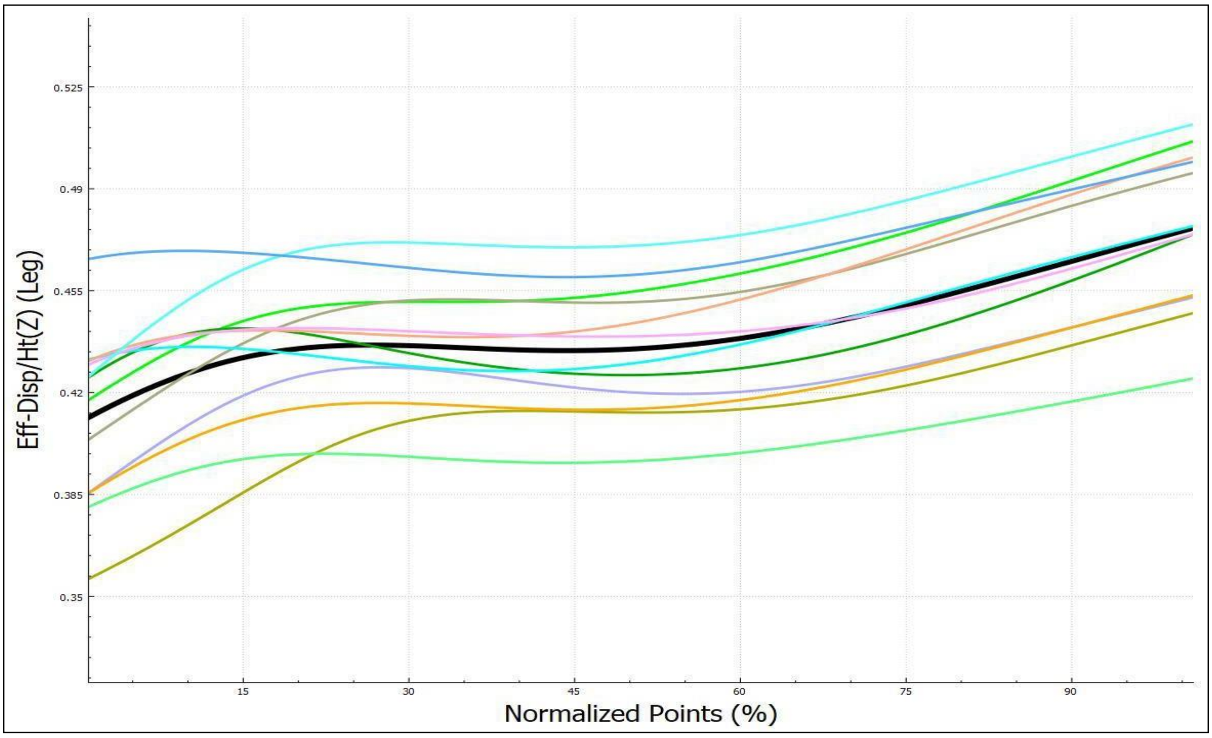

Figure 18.3.9: *Signal graph of the Leg effector displacement waveforms in the Z-dimension across the acceleration phase. Individual bowler's mean waveforms are represented by each colour with the group mean waveform represented by the bold black line.*

18.4 Leg-X to pitch length variability correlation plot

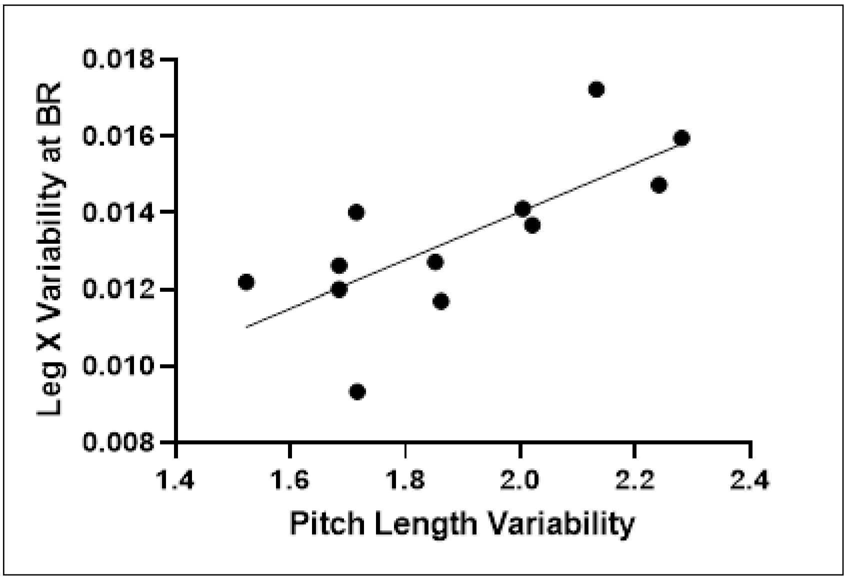

Figure 18.4.1: Leg-X variability at ball release to pitch length variability correlation plot.

Figure 18.4.1 correlation plot shows a strong correlation between Leg-X variability at ball release to pitch length variability (R = .733, R^2 = .537, p = 0.007).

18.5 Trunk-Z to pitch length variability correlation plot

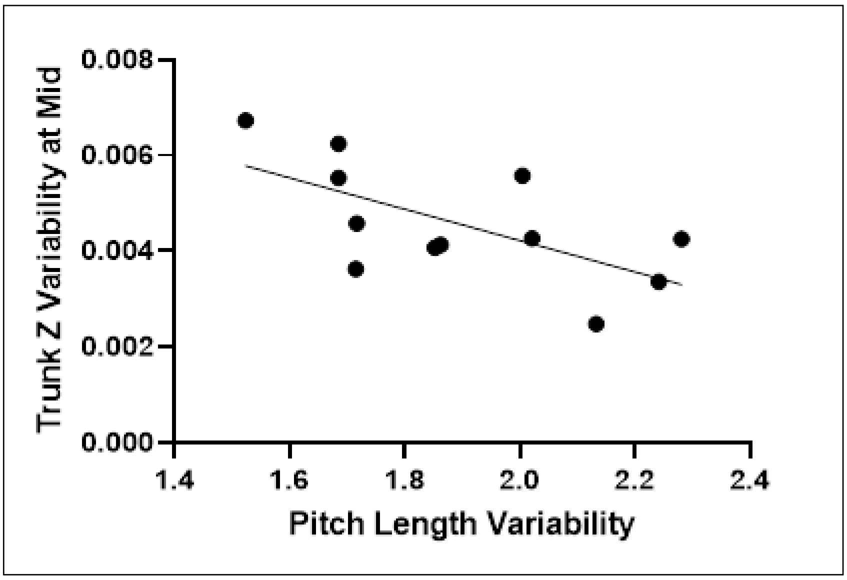

Figure 18.5.1: *Trunk-Z variability at mid acceleration phase to pitch length variability correlation plot.*

Figure 18.5.1 correlation plot shows a moderate correlation between Trunk-Z variability at mid acceleration phase to pitch length variability (R = -.644, R^2 = .414, p = 0.024).

18.6 Loughborough ethics approval letter

Research & Enterprise Office
Loughborough University
Leicestershire LE11 3TU UK

T: 01509 222222
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Loughborough University

Dear Mark

PROJECT TITLE: Cricket fast bowling: Understanding variability

PROJECT ID: 3156

On behalf of the Ethical Approvals (Human Participants) Sub-Committee I can confirm that the proposal 2021-3156-2596 has full ethical approval.

Where possible we recommend that studies are conducted online. However, if it is necessary to conduct face-to-face research you must ensure that you follow the latest Government guidance on COVID-19. In addition, there is a Health and Safety Process that must be completed after the ethical review. You are not permitted to begin data collection which requires any face-to-face interactions with participants in person without the appropriate COVID-19 risk assessments signed by the School Safety Officer and Julie Turner, in the Health and Safety Office, and with approval from the Dean.

Studies can be moved online without requiring an amendment, unless this substantially changes the study in which case an amendment is required.

If in the future you wish to make any amendments to the study please submit an amendment using the relevant form.

You are required to report to the Sub-Committee any incidents that have an adverse effect using the Adverse Events Report form in LEON.

This approval applies until 01/01/2023. If the study continues beyond this date you should submit a request for an extension.

Kind Regards,

Jackie

on behalf of Ethical Approvals (Human Participants) Sub-Committee

18.7 ISBS 2022 publication

Published in the 40th International Society of Biomechanics in Sports Conference, Liverpool, UK:

July 19-23, 2022

Sutherland, A., King, M., Hiley, M., McErlain-Naylor, S., & Taylor, S. (2022). VARIABILITY OF BALL RELEASE PROPERTIES AND PITCH LENGTH ACCURACY IN CRICKET FAST BOWLING. *ISBS Proceedings Archive*, *40*(1), 695. https://commons.nmu.edu/cgi/viewcontent.cgi?article=2412&context=isbs

VARIABILITY OF BALL RELEASE PROPERTIES AND PITCH LENGTH ACCURACY IN CRICKET FAST BOWLING

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Accurate ball pitch length in cricket fast bowling is potentially achieved from a redundant combination of four ball release parameters. Yet, it is unknown how parameter co-variations affect pitch accuracy. This study investigates whether pitch length variance is determined by coordinated ball release parameter co-variability. Twelve fast bowlers performed 18 trials at a target length and ball kinematics were captured from an indoor 3D camera setup. Multi-linear regression analysis showed that the four release parameters accounted for 79% of pitch length variance, where vertical velocity variance accounted for the most variance. When each release parameter was independently shuffled across trials, a pitch length model showed no indication of coordinated co-variability between input parameters. Therefore, pitch length accuracy was achieved by independent control of vertical velocity.

KEYWORDS: pitch accuracy, variability, co-variability, fast bowling

INTRODUCTION: Attributes of maximum ball release speed and pitch accuracy (i.e., successful attainment of intended ball projection length, or flight range) in cricket fast bowling are advantageous, because this combination leads to batting errors of the opposing team. Ball release speed has been a primary focus of bowling biomechanics research (i.e., Portus et al., 2004; Worthington et al., 2013), while the inter-relatedness of ball release parameters that contribute to pitch accuracy have received less focus (Glazier & Wheat, 2014).
As such, there is a knowledge gap related to pitch accuracy. Bowling accuracy has been investigated whilst exploring performance characteristics between different levels of expertise (Phillips et al., 2012), effect of differing pitch lengths on junior performance (Harwood et al, 2018) and the effects of dehydration on ball speed and accuracy (Devlin et al., 2001). However, no reported studies attempted to investigate how a bowler controls pitch length accuracy. Only Harwood et al. (2018) reported the effect of different pitch lengths on release parameter attributes in children, noting a change in ball release angle explains most of the variance in pitch length.
Therefore, it is currently unknown how fast bowlers minimise variability of ball release parameters to control pitch length accuracy in adults. Indeed, performance variability can be mitigated if contributing elements cooperate (e.g., coordination co-variance of parameters). Phillips and colleagues (2012) noted for task demands such as accuracy, the valuation of technique would provide valuable insights into fast bowling performance. For example, how does a bowler control the inherent variability of a redundant combination of ball release parameters: (i) horizontal velocity (ii) vertical velocity (iii) horizontal position, and (iv) vertical position? There is a gap in the current literature on cricket fast bowling that relates to the effect ball release and velocity on pitch length accuracy. Therefore, this study aims to explore variation and co-variation of these four release parameters and identify the key parameters related to pitch length accuracy.

METHODS: Twelve male fast bowlers (mean ± standard deviation: age 19 ± 1; height 1.87 ± 0.04 m; body mass 82.4 ± 11.5 kg) who were members of the Marylebone Cricket Club University team were tested in accordance with the guidelines outlined by the Loughborough University Ethical Advisory Committee. Each bowler bowled a minimum of 18 good (participant determined) length deliveries captured by an 18 camera VICON MX system (250 Hz, OMG Plc, Oxford, UK) in an indoor cricket specific facility. Forty-two retro-reflective markers were attached to the body as specified by Worthington et al. (2013) and two additional 15 x 15 patches of reflective tape were placed on each hemisphere of the ball. Participant marker data was filtered by using a fourth order low pass Butterworth filter at 15Hz. The global coordinate system z-axis was recorded in the upward vertical direction, the y-axis was defined to run parallel to the long axis of the cricket pitch (middle stump to middle stump), with the positive direction being measured from the batter's end. Ball release was determined as the first visual frame where the selected ball marker exceeds 50 mm of horizontal separation of distance from the virtual landmark. The virtual landmark was created as an expression 20% separation gap between the hand and ball marker. This method was determined as an appropriate measure to obtain ball release after a sensitivity analysis and comparison to the method of Worthington at al. (2013).
Ball flight properties were calculated using simple projectile laws based on constant acceleration (over ten frames post ball release), negligible air resistance and computed within the global coordinate system. Pitch length was calculated from the four ball release parameter inputs of (i) horizontal velocity (Vz); (ii) vertical velocity (Vy); (iii) horizontal position (Py); and (iv) vertical position (Pz). Horizontal and vertical resultant ball release velocity were recorded from the average of 10 frames post ball release. Horizontal position (recorded relative to the middle stump from the bowler's end) and vertical release position (ball height) were also recorded at ball release in the global coordinate system. The equation used to calculate pitch length from a standard 22-yard pitch (20.12 m) was:

$$Pitch\ Length = 20.12 - \frac{(-Vz - \sqrt{Vz^2 + (2 \times 9.8 \times Pz)})}{-9.8} \times Vy - Py$$

Box plots of ball release parameters and pitch length for the bowling group were used to describe normal distribution of results (Figure 1). Mean pitch length was assumed to represent their goal pitch length and standard deviations were calculated as estimates of bowler variability. The first 18 trials per bowler were used to determine accuracy and ball release parameter values, with an additional ball added in place of any identified outlier trial. Outliers were determined by conducting a Grubbs' test.

Matlab v.2021a (The MathWorks Inc., Natick, MA, USA) was used to complete a cyclical simulated release parameter shuffle, whereby each parameter's individually recorded value was cyclically shuffled 18 times for each of the 18 deliveries. The other release parameter values remained un-shuffled. This shuffle determined the random pitch length variability contribution (standard deviation) of each parameter. Index of Cooperation as used by Kusafuka et al. (2021) was then adopted to indicate parameter co-variability. IBM SPSS Statistics v. 27 (IBM, Armonk, NY, USA) was used to perform a multi-linear regression analysis to explain pitch length variability (dependent variable). The percentage of variance in the dependent variable explained by the independent variables within the regression equation was determined by the R2 value. P-value of <0.05 was used to determine significance of the regression model and independent variables in describing variance of the dependent variable.

RESULTS: Group average pitch length mean, and group average standard deviation was 6.12 ± 1.89 m. Mean vertical velocity variability (1.11 $m \cdot s^{-1}$) was greater than horizontal velocity (0.81 $m \cdot s^{-1}$). However, mean vertical position variability (0.02 m) was less variable than the mean horizontal position variability (0.14 m).

A multi-linear regression model successfully predicted pitch length variance from four ball release parameters ($F(4, 7) = 6.55$, $p = .016$, $R2 = .789$). Of the four predictor variables investigated, only vertical velocity variability ($\beta = 1.313$, $t\text{-}(7) = 4.437$, $p < .05$) was significant. The surrogate data set and output of modelled (cyclical shuffle) pitch length found that pitch accuracy was not significantly more (or less) variable than random variance of model input parameters (± 1.89 m: After shuffling the model inputs (ball release parameters) across trials the average pitch length variance was 1.90 m for vertical velocity, 1.91 for horizontal velocity m, 1.88 m for vertical position, 1.90 m for horizontal position, and 1.88 m for the horizontal/vertical velocity double shuffle). In support, an Index of Cooperation (IC) revealed a lack of co-variability on pitch length variance (vertical velocity 1.00, horizontal velocity 1.01, vertical position 0.99, horizontal position 1.01, and vertical/horizontal velocity 1.00).

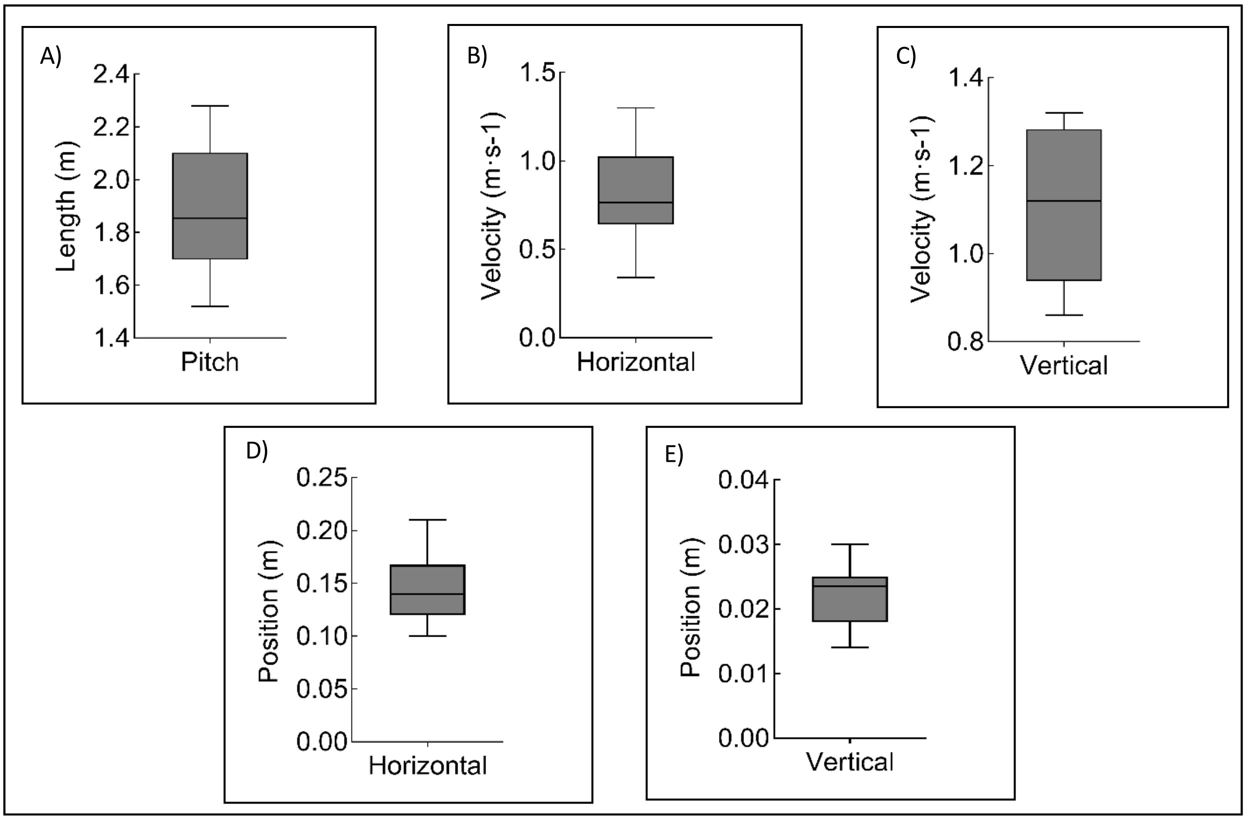

Figure 1: Box and whisker plots showing the group median and quartile distribution: a) pitch length standard deviation b) horizontal velocity standard deviation c) vertical velocity standard deviation d) horizontal position standard deviation, and e) vertical position standard deviation.

DISCUSSION: This study quantified the impact of the four ball release parameters on pitch length variability. Group accuracy was found to be (1.89 m) which was only slightly less accurate than data collated by Cork et al. (2012) (1.76 m). The most variable ball release parameter was found to be vertical velocity which varied by (1.11 m·s-1) amongst the bowling group. Release position standard deviation in contrast varied much less (horizontal position 0.14 m, vertical position 0.02 m) and was comparable to results gathered by Cork et al. (2012) with a horizontal position standard deviation of 0.27 m and Salter et al. (2007) with a vertical release position of 0.03 m. The four ball release parameters were then run through a multi-linear regression. Horizontal velocity variability, vertical velocity variability, horizontal release position variability and vertical release position variability, together explained 79% of the variance in pitch length. Vertical velocity variance was found to significantly describe pitch length control. This result was not unexpected, as Kusafuka et al. (2021) and Harwood et al. (2018) both noted ball release angle played a role in explaining baseball pitching accuracy and cricket bowling pitch length. However, the lack of significance of other parameters suggests vertical velocity is the prominent predictor and influencer of pitch length control. Thus, for bowlers to bowl an accurate length reducing vertical velocity appears to be important. The lack of evidence indicating ball release positioning's influence on pitch length variability too was not unexpected, because they are deemed as constrained variables. Vertical release positioning is constrained by the physical height of the bowler and any fluctuations in the magnitude have a very limited influence on flight time and range, as demonstrated in underarm throwing by Dupuy et al. (2000). The horizontal release position is also constrained by the bowling crease, whereby the magnitude only varied by 0.14 m in the group, delivering the ball 1.65 m from the bowler's stumps or almost exactly over the bowling crease at 1.6 m. Harwood et al. (2018) noted junior bowlers showed no indication of adaptive change of their foot position when bowling different lengths and the small change in release position of 0.14 m in this dimension supports that result.

However, it was the lack of evident coordinated co-variation between the release parameters that was the most intriguing result. Index of Cooperation results (vertical velocity 1.00, horizontal velocity 1.01, vertical position 0.99, horizontal position 1.01 & vertical/horizontal velocity 1.00) showed no indication of cooperation between any of the release parameters, as there was no distinct difference in Index of Cooperation scores. Index of Cooperation scores should be regarded as an expression of cooperative contribution to the degree of variability (Kusafuka et al., 2021), and a score close to one poses no distinction between the performed and simulated cyclical results. Thus, the results from this shuffle demonstrate very little if any cooperation is occurring to reduce pitch length variability. Kusafuka et al. (2021) found similar results in baseball pitching vertical displacement, whereby scores close to one were likely due to their limited impact on pitch location. This likely indicates, as with baseball pitching, bowling pitch length accuracy is highly influenced by vertical velocity variability and that pitch variability is unlikely to be adapted or controlled through coordinated co-variation.

CONCLUSION: This study aimed to investigate how cricket fast bowlers controlled their pitch length accuracy from the variability of four ball release parameters. There was found to be little coordinated co-variability amongst the release parameters in reducing pitch length variance. This indicates the release parameters work independently from each other, with vertical velocity having the largest impact on pitch length variance. Therefore, reducing vertical velocity variability is advantageous in improving pitch length accuracy and, as such, understanding how the bowler controls vertical velocity variability should be of focus moving forward.

REFERENCES:

Devlin, L. H., Fraser, S. F., Barras, N. S., & Hawley, J. A. (2001). Moderate levels of hypohydration impairs bowling accuracy but not bowling velocity in skilled cricket players. *Journal of Science and Medicine in Sport, 4*(2), 179-187. https://doi.org/10.1016/S1440-2440(01)80028-1

Dupuy, M. A., Motte, D., & Ripoll, H. (2000). The regulation of release parameters in underarm precision throwing. *Journal of Sports Sciences, 18*(6), 375–382. https://doi.org/10.1080/02640410050074304

Glazier, P. S., & Wheat, J. S. (2014). An integrated approach to the biomechanics and motor control of cricket fast bowling techniques. *Sports Medicine, 44*(1), 25-36. https://doi.org/10.1007/s40279-013-0098-x

Harwood, M. J., Yeadon, M. R., & King, M. A. (2018). Does shortening the pitch make junior cricketers bowl better? *Sports Medicine and Biomechanics, 36*(17), 1972-1978. https://doi.org/10.1080/02640414.2018.1428884

Kusafuka, A., Kudo, K., & Nakazawa, K. (2021). Control of accuracy during movements of high speed: Implications from baseball pitching. *Journal of Motor Behavior*, *1*(12). https://doi.org/10.1080/00222895.2021.1960789

Phillips, E., Portus, M., Davids, K., & Renshaw, I. (2012). Performance accuracy and functional variability in elite and developing fast bowlers. *Journal of Science and Medicine in Sport, 15*(2), 182-188. https://doi.org/10.1016/j.jsams.2011.07.006

Portus, M. R., Mason, B. R., Elliott, B. C., Pfitzner, M. C., & Done, R. P. (2004). Technique factors related to ball release speed and trunk injuries in high performance Cricket fast bowlers. *Sports Biomechanics, 3*(2), 263-284. https://doi.org/10.1080/14763140408522845

Salter, C. W., Sinclair, P. J., & Portus, M. R. (2007). The associations between fast bowling technique and ball release speed: A pilot study of the within-bowler and between-bowler approaches. *Journal of Sports Sciences, 25*(11), 1279-1285. https://doi.org/10.1080/0264041060109682

Worthington, P. J., King, M. A., & Ranson, C. A. (2013). Relationships between fast bowling technique and ball release speed in cricket. *Journal of Applied Biomechanics, 29*(1),78–84. https://doi.org/10.1123/jab.29.1.78