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The mechanics of front leg loading during cricket fast bowling: delivery variations, spell demands, and the effects of strength training

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ABSTRACT

The goal of fast bowling in cricket is to dismiss a batsman for as few runs as possible. To assist this goal, fast bowlers will attempt to maximise ball release velocity (BRV) to decrease the decision-making and stroke execution time of the opposing batsmen. Fast bowlers will also employ various delivery lengths (i.e. short, good and full) to assist in affecting a batsman's stroke execution. Several issues remain to be addressed with regards to the biomechanical assessment of fast bowling. This is particularly evident when analysing fast bowling performance (i.e. BRV), the implications of front foot loading (i.e. vertical and braking ground reaction forces [GRFs]) and the associated kinematics (i.e. knee, shoulder, and trunk angles). The biomechanics of delivery lengths, spell demands, periodised strength training interventions, and the potential to conduct biomechanical analyses during match-play, have received limited attention within the scientific literature with respect to fast bowling. Therefore, the purpose of this thesis was four-fold: 1) determine if changes in delivery length necessitate acute alterations in fast bowling biomechanics and BRV; 2) identify whether an extended eight-over bowling spell resulted in changes in biomechanics or performance within different delivery lengths; 3) assess the chronic effects of a periodised strength training intervention upon front foot loading and performance in fast bowlers; and 4) investigate the reliability and validity of inertial measure unit (IMU) derived trunk and tibia accelerations with respect to GRF during front foot contact (FFC). This series of studies provides valuable information about the implications of delivery length, spell demands and the influence of strength training upon fast bowling biomechanics and performance, as well as the first investigation on the reliability and validity of segmental load measures in comparison to FFC GRF for fast bowlers.

Study 1 outlined that changes in delivery length did not necessitate alterations in fast bowling biomechanics or BRV. Therefore, it appeared that fast bowlers were able to employ different delivery lengths without significant changes in their technique, which is ultimately beneficial to the goal of fast bowling. Study 2 demonstrated that an extended eight-over bowling spell did not result in any biomechanical or performance differences when comparing the average of the first and last three overs. Fast bowlers were able to maintain their technique and FFC loading patterns during a single extended bowling spell, which provided support to current bowling workload monitoring practices. Study 3 demonstrated that an eight-week periodised strength training program can elicit significant improvements in strength and lower-limb eccentric capacity among fast bowlers. However, this had minimal impact upon FFC GRFs, with no significant changes in BRV between pre- and post-testing. These findings may indicate that a combined approach of strength and skill training is necessary for improvements in BRV. Study 4 documented that IMU derived trunk and tibia segment accelerations were reliable, but not a valid representation of GRF during FFC. With further investigation, segment acceleration could be a useful measure for fast bowling performance and biomechanics, but does not provide an appropriate representation of GRF during FFC.

DECLARATION

I certify that this thesis does not, to the best of my knowledge and belief:

(i) incorporate without acknowledgement any material previously submitted for a degree or diploma in any institution of higher education;

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Samuel J Callaghan

29th September 2017

USE OF THESIS

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To my friend and principle supervisor, Soph, I cannot think of one chat, catch-up or ‘meeting’ in which you weren’t teaching me something new or had me laughing. I am so thankful that you took a punt on a big goofy cuddly bear and welcomed me into your circle (lets me honest, not everybody makes the cut). Your depth of knowledge on all things biomechanics, strength and conditioning, statistics, research design, and the list goes on, is truly amazing. If I am able to become one-fifth the researcher, teacher and leader you are, I will be very happy with my achievements. A special thanks must also go to Cat, for allowing me to steal you away so often and crash your date night, although sometimes I felt like you had to steal Cat back from me. I can’t thank you enough for what you have done for me and I know we will continue to be great friends first and colleagues second. In response to your request to leave a rule behind for future students, I don’t think I have a rule, more some friendly advice; make sure you enjoy the little wins along the way or you won’t make it out!!! If you hold out for the big wins (e.g. presenting your proposal, end of data collection or final submission) you will die of thirst, so make sure you take time to appreciate and celebrate the little things, like finding out your local does a great pie and pint lunch special and has free wifi, or that the uni has an eResearch laboratory that nobody knows about, it is all about the little wins!!

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something that I am very grateful for. To Jonesy and Q I don’t think you understand how much you have both taught me, not only your skills within your work but your professionalism is something that I will try to emulate within my own career. To the rest of the team; Joey, Swampie, Stars, Stewy, JL, Griff, Fitzy, Yobbie, Wassy, Ben and Mel, and anybody else that I may have missed, thank you for always making my time at the WACA most enjoyable.

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Mr Tufano “cuddle buddy” your willingness to help a friend out regardless of the effort that it requires from you, even if it was a 3 am airport run, just demonstrates what a great person you are….or should I say boss?? To my partner in Crime, the lego man himself, Timothy Pulverenti, having someone to struggle through a PhD is an essential to completing this monumental task, and I lucked out when we teamed up. Thank you for always being there to lend a helping hand, beer or kebab whatever the situation called for. I won’t be mentioning our adventures in print, but I can’t wait till we head back to hoepentus. To Grant, Cassius, Brendo, Aaron, Travis, Val, Jo, Audrey, Tina, B, Pauly, Big V, Harry, Keller, Andrew, Cassio, Matheius, Ellen, Siham and everybody else that I have forgotten, thank you for the laughs, great company and adventures over the past three and half years.

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LIST OF ABBREVIATIONS

Abbreviation	Definition
%	Weight lifted as percentage of one repetition maximum
°	Degree
1D	One-dimensional
3D	Three-dimensional
AL	Altitude landing
ANOVA	A repeated measures analysis of variance
Avg	Average
B	Band assisted
BB	Barbell
BLR	Braking loading rate
BR	Ball release
BRV	Ball release velocity
BW	Body weight
CMJ	Counter movement jump
COM	Centre of mass
CV	Coefficient of variance
DB	Dumbbell
DLDL	Double leg drop landing
d	Cohen’s effect size
FFC	Front foot contact

FP	Force plate
GPS	Global positioning satellite
GRF	Ground reaction force
h	Hours
Hz	Hertz
ICC	Intra-class correlation coefficient
IMTP	Isometric mid-thigh pull
IMU	Inertial measurement unit
JH	Jump height
kg	Kilograms
km	Kilometre
$km \cdot h^{-1}$	Kilometres per hour
LJ	Left joint centre
Load	Set weight lifted
m	Metre
$m \cdot s^{-1}$	Metres per second
n	Number of participants
N	Newtons
$N \cdot BW^{-1}$	Newtons per body weight
$N \cdot s$	Newtons per second
$N \cdot s \cdot BW^{-1}$	Newton seconds per body weight
$N \cdot s^{-1} \cdot BW^{-1}$	Newtons per second per body weight
PBF	Peak braking force

PF	Peak force
Post	Following the completion of the intervention
PP	Peak power
Pre	Prior to the commencement of the intervention
PVF	Peak vertical force
RDL	Romanian deadlift
RJ	Right joint centre
S1	Session one
S2	Session two
SD	Standard deviation
SLDL	Single leg drop landing
SPM	Statistical parametrical mapping
T20	Twenty20
TEM	Typical error of measurement
VLR	Vertical loading rate
$W \cdot BW^{-1}$	Watts per body weight

At the request of the author,

the publications list is unavailable in this version of the thesis.

CHAPTER ONE

General Introduction and Aims of the Thesis

Sets out the research objectives and provides an overview of the thesis structure

1.1 Background

Cricket is a bat and ball game played between two teams consisting of eleven players, and is a unique sport in that there are different match formats (i.e. Twenty20 [T20], one-day and multi-day matches). What is consistent between all match formats are the required skills of players, be that batting, bowling or fielding. Specifically for fast bowlers, they attempt to dismiss an opposing batsman for as few runs as possible, often via maximising ball release velocity (BRV). An increased BRV can decrease the decision-making and stroke execution time of the opposing batsmen (Bartlett, Stockill, Elliott and Burnett, 1996; Stuelcken, Pyne and Sinclair, 2007). Another strategy is the use of various delivery lengths (i.e. short, good and full) to affect a batsman's stroke execution (Justham, West, Harland and Cork, 2006; Weerakkody and Allen, 2016). To generate a high BRV while targeting various delivery lengths fast bowlers will complete a run-up to the crease before an explosive leap into the delivery stride. During the delivery stride, bowlers will experience high ground reaction forces (GRFs) experienced at rear and front foot contact (FFC), in both the vertical and braking (horizontal) planes (Hurrion, Dyson and Hale, 2000).

Numerous investigations have assessed the biomechanical variables associated with increased BRV (Glazier, Paradisis and Cooper, 2000; Phillips, Portus, Davids, Brown and Renshaw, 2010; Portus, Mason, Elliott, Pfitzner and Done, 2004; Wormgoor, Harden and McKinon, 2010; Worthington, King and Ranson, 2013b). Variables such as run-up velocity (Glazier and Worthington, 2014), trunk (Phillips et al., 2010), shoulder (Worthington et al., 2013b) and knee (Portus et al., 2004) actions, and the vertical and braking GRF during FFC

(King, Worthington and Ranson, 2016; Middleton, Mills, Elliott and Alderson, 2016) have demonstrated strong relationships to BRV. However, despite the use of various delivery lengths to aid in dismissing opposing batsmen, there has been limited scientific evaluation of any potential biomechanical differences in deliveries targeting different lengths among fast bowlers (Hazari and Warsi, 2015; Roca, Elliott, Alderson and Foster, 2006).

The different match formats within cricket each place unique physiological stressors upon fast bowlers (Petersen, Pyne, Dawson, Portus and Kellett, 2010; Petersen, Pyne, Portus and Dawson, 2011). Specifically, the multi-day match format dictates that fast bowlers will be required to perform numerous bowling overs, sometimes in excess of 50 overs, typically within extended bowling spells (J. Orchard, T. James, M. Portus, A. Kountouris and R. Dennis, 2009; Portus et al., 2004). Previous research has demonstrated that regardless of the level of competition or age, fast bowlers should be able to maintain BRV during a single or two extended bowling spells (Burnett, Elliott and Marshall, 1995; Crewe, Campbell, Elliott and Alderson, 2013; Duffield, Carney and Karppinen, 2009; Portus, Sinclair, Burke, Moore and Farhart, 2000; Schaefer, O'Dwyer, Ferdinands and Edwards, 2017). However, the influence of an extended bowling spell upon the underlying biomechanical factors previously associated with BRV (i.e. vertical GRF, braking impulse and shoulder angle at ball release) requires further investigation (King et al., 2016; Portus et al., 2004; Worthington et al., 2013b). Further to this, no research to date has investigated the implications of different delivery lengths upon a fast bowler’s biomechanics or BRV throughout several overs. This is despite the use and importance of varying delivery length within match-play to assist in dismissing opposing batsmen. This may be particularly important as kinematic variations may present as advanced cues to a batsman (Brenton et al., 2016). In addition to this, the ability to produce similar GRF between different delivery lengths is also of practical importance when considering the need to represent loading during workload monitoring practices among fast bowlers

It is important to note, that regardless of any possible changes in bowling biomechanics within a spell, fast bowlers are still required to overcome high FFC GRFs each delivery (Hurrion et al., 2000; King et al., 2016; Phillips et al., 2010; Worthington, King and Ranson, 2013a). As a result, it is recommended that fast bowlers possess high levels of muscular strength to not only withstand the requirements of match-play, but ensure maximal effort each delivery (Mukandi, Turner, Scott and Johnstone, 2014; Stronach, Cronin and Portus, 2014a, 2014b). However, to date there has only been two scientific investigations which have analysed the implications of a training intervention upon BRV (Petersen, Wilson and Hopkins, 2004; Wickington and Linthorne, 2017). Both Wickington and Linthorne (2017) and Petersen et al. (2004) found that a special resistance training program utilising under-weight and over-weight cricket balls failed to significantly improve BRV in well-trained and senior club cricketers. Previous research in baseball has suggested that such special resistance training should be performed after general and specific training has been performed to increase throwing velocity (van den Tillaar, 2004). Therefore, increases in strength, particularly lower-limb strength, which has previously been suggested to be linked to BRV (Stronach, Cronin, & Portus, 2014) may be necessary before any technique changes could be incurred; however, further research is needed to assess this hypothesis.

Consideration is needed when interpreting the current scientific research regarding the biomechanics and performance of fast bowlers, as the majority of investigations have been undertaken within the laboratory (Ferdinands, Kersting and Marshall, 2009; Glazier and Worthington, 2014; Middleton et al., 2016; Portus et al., 2004; Worthington et al., 2013b). Testing within a laboratory allows for a more detailed analysis of the fast bowling action; however, this environment may not appropriately represent the unique match conditions of cricket. The development of new technologies such as inertial measurement units (IMUs), which contain tri-axial accelerometers, gyroscopes and magnetometers, may represent an alternative to current laboratory-based methods which allow for field-based assessment of the fast bowling action within match-play, however they have yet to be validated.

As previously stated, the role of a fast bowler is to attempt to dismiss a batsman for as few runs as possible. To achieve this, fast bowlers will attempt to maximise and maintain BRV, while utilising changes in delivery length. However, scientific research is necessary to assess whether variations in delivery length lead to distinctive changes in biomechanics and performance, within acute short and extended bowling spells. This is coupled with the need to investigate the implications of strength and conditioning interventions based upon scientific research upon fast bowling biomechanics and BRV. Consideration for methods of field-based assessment of fast bowling is also warranted. The research studies aimed to address these issues.

1.2 Aims of the Research Studies

As a result of the current gaps in the literature, this thesis sought to examine:

a) The biomechanical differences (front foot loading, knee, shoulder and trunk kinematics, and BRV) between different delivery lengths (i.e. short, good and full) among fast bowlers;

b) If changes to fast bowling front foot loading, knee, shoulder and trunk kinematics, and the resulting implications on BRV occur during a single, eight-over bowling spell among fast bowlers;

c) The effect of a strength training intervention on front foot loading and performance (assessed by BRV) among fast bowlers; and

d) The validity and reliability of IMU derived trunk and tibia accelerations with respect to FFC GRF for potential use during training and match conditions.

1.3 Research Questions and Hypotheses

Study One

Research Question: Are there significant differences in discrete and continuous biomechanical variables, and BRV between different delivery lengths (short, good, and full) among fast bowlers?

Hypothesis: There will be significant differences in discrete and continuous biomechanical variables, and BRV between different delivery lengths (short, good, and full) among fast bowlers.

Study Two

Research Question: Does fast bowling discrete and continuous biomechanical variables and BRV change during an eight-over bowling spell within fast bowlers?

Hypothesis: There will be no change in BRV throughout the eight-over bowling spell for fast bowlers. However, changes in discrete and continuous biomechanical variables will be evident for fast bowlers.

Study Three

Research Question: Does an eight-week strength training intervention induce changes in fast bowling discrete and continuous biomechanical variables and BRV in fast bowlers?

Hypothesis: It is hypothesised that the eight-week training intervention will change strength, power and eccentric capacity measures, as measured by the isometric mid-thigh pull, counter-movement jump, and double and single leg drop landings tasks, respectively. This will lead to changes in GRF during FFC. It is further hypothesised that these changes in GRF will result in an alteration in BRV for fast bowlers.

Study Four

Research Question: Are IMU derived trunk and tibia mounted accelerations a reliable and valid representation of GRF during FFC?

Hypothesis: It is hypothesised that the accelerometer data from both the trunk and tibia mounted IMUs will be a reliable and valid representation of discrete and continuous GRF measures, as determined and compared to the criterion measure of an in-ground tri-axial force plate during FFC for fast bowlers.

1.4 Significance of the Research

No research to date has appropriately analysed the biomechanical variations between various delivery lengths (i.e. short, good and full) and any possible resulting implications upon performance (i.e. BRV). This is despite match-play tactics dictating that fast bowlers will employ various delivery lengths in an attempt to disrupt the stroke execution of an opposing batsman. As selected biomechanics have been associated with superior fast bowling performance, it is essential to investigate the effects of changes in delivery lengths during an short or extended bowling spell upon the biomechanics adopted by fast bowlers. This is particularly pertinent when considering the high GRFs experienced during FFC which facilitate the ability to rapidly decelerate during the delivery stride, creating large amounts of available kinetic energy to transfer through to ball release. In addition, research must also determine whether a periodised strength training intervention can enhance aspects of a fast bowler's biomechanics, resulting in improved BRV. Greater consideration is also needed regarding the ecological validity of laboratory-based testing, particularly with respect to the different match formats. As a consequence, it is essential that new technologies, such as IMUs, which may offer a possible solution to the lack of field-based assessments of the fast bowling action, are appropriately investigated.

1.5 Limitations

The limitations of this thesis are as follows:

Study One

a) *Classification of different delivery lengths*

The large ranges and consecutive sequencing of the three different delivery lengths (short, good and full) (Duffield et al., 2009; McNamara, Gabbett, Blanch and Kelly, in press) may have led to deliveries pitching only centimetres apart being classified as different lengths, while other deliveries pitching metres apart were classified as being the same length.

b) *Laboratory-based testing*

The use of laboratory-based testing may limit the ecological validity of the study. However, laboratory testing allowed for a more detailed analysis of the fast bowling action, and has previously been used within the literature (Glazier and Worthington, 2014; King et al., 2016; Worthington et al., 2013b).

Study Two

a) *Classification of different delivery lengths*

The large ranges and consecutive sequencing of the three different delivery lengths (Duffield et al., 2009; McNamara et al.) may have led to deliveries pitching only centimetres apart being classified as different lengths, while other pitching metres apart being determined as the same length.

b) Laboratory-based testing

The use of laboratory-based testing may limit the ecological validity of the study. However, laboratory testing allowed for a more detailed analysis of the fast bowling action, and has previously been used within the literature (Glazier and Worthington, 2014; King et al., 2016; Worthington et al., 2013b).

c) Participant numbers

The participant numbers utilised in this study were low (n = 9), although they were similar to previous research analysing the effects of an extended bowling spell upon fast bowling biomechanics and BRV (Burnett et al., 1995; Devlin, Fraser, Barras and Hawley, 2001; Duffield et al., 2009).

Study Three

a) Classification of different delivery lengths

The large ranges and consecutive sequencing of the three different delivery lengths (Duffield et al., 2009; McNamara et al.) may have led to deliveries pitching only centimetres apart being classified as different lengths, while other pitching metres apart being determined as the same length.

b) Laboratory-based testing

The use of laboratory-based testing may limit the ecological validity of the study. However, laboratory testing allowed for a more detailed analysis of the fast bowling action, and has previously been used within the literature (Glazier and Worthington, 2014; King et al., 2016; Worthington et al., 2013b).

c) Participant numbers

The participant numbers utilised in this study are low (n = 10), however they are similar to previous strength training studies in athletic populations (Nimphius, McGuigan and Newton, 2012; Petersen et al., 2004), and are representative of the typical number of fast bowlers within an Australian state pathway program

d) No kinematic data

No kinematic data was collected for this study, hence future research should assess whether a periodised strength training program can elicit changes in a fast bowler's kinematics.

Study Four

a) Standard of play

Recreational fast bowlers were used in this study, as opposed to elite or high performance bowlers. Nonetheless, the use of amateur and recreational athletes is common among reliability and validity studies and typically allows for a more robust analysist due to greater within-participant variability (Nedergaard et al., 2017; J. Tran, Netto, Aisbett and Gastin, 2010; Wundersitz, Netto, Aisbett and Gastin, 2013).

b) Sample frequency

The IMUs utilised within this study had a low sample frequency (75 Hz). However, this sample frequency is similar to that of other commercially based accelerometers (100 Hz) which have been investigated within the literature due to their use in field-based team sports (Meyer et al., 2015; Nedergaard et al., 2017; Weerakkody and Allen, 2016).

c) Movement artefact

The degree of movement artefact present as a result of the IMU mounting on the trunk and tibia may have influenced the results. Nevertheless, all appropriate measures were taken to limit the degree of movement artefact, which was in accordance with previous research (Cloete and Scheffer, 2010; Kavanagh and Menz, 2008).

1.6 Delimitations

The delimitations of the thesis are as follows:

Study One

a) Gender

Participants recruited for the current study were restricted to males.

b) Standard of play

Only participants currently or previously a part of a state development pathway or playing premiere league within a state based competition were recruited for this study.

c) Testing equipment

An XSENS motion analysis system was used to record each trial. The XSENS motion analysis system has previously been found to be a reliable and valid means of assessing joint angles in dynamic movements (Cloete and Scheffer, 2010; Kok, Hol and Schön, 2014). An in-ground three-dimensional (3D) force plate was used to collect GRF data during FFC of the delivery stride for each delivery. A calibrated Stalker Pro II speed radar gun was used to determine BRV each delivery.

Study Two

a) Gender

Participants recruited for the current study were restricted to males.

b) Standard of play

Only participants currently or previously a part of a state development pathway or playing premiere league within a state based competition were recruited for this study.

c) Testing equipment

A XSENS motion analysis system was used to record each trial. The XSENS motion analysis system has previously been found to be a reliable and valid means of assessing joint angles in dynamic movements (Cloete and Scheffer, 2010; Kok et al., 2014). An in-ground 3D force plate was used to collect GRF data during FFC of the delivery stride for each delivery. A calibrated Stalker Pro II speed radar gun was used to determine BRV each delivery.

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d) Strength training intervention

Each participant undertook the same exercises, sets and repetitions within the training intervention.

Study Four

a) Gender

Participants recruited for the current study were restricted to males.

b) Standard of play

Only recreationally trained participants who were proficient in the movements of the fast bowling action were recruited for this study.

c) Testing equipment

An in-ground tri-axial force plate was used to collect GRF data during FFC of the delivery stride for each delivery. Two wireless, time synchronised IMUs were used to collate trunk and tibia mounted accelerations each delivery.

1.7 General Overview of the Following Chapters

This thesis consists of seven total chapters. Initially, a detailed review of cricket fast bowling literature is presented in Chapter Two. Thereafter, a series of four experimental studies are presented. Chapter Three presents the results of the first study which explores the acute implications of changes in delivery length upon fast bowling biomechanics and BRV. Chapter Four contains the second study which progresses to investigate the acute implications of a match-specific eight-over bowling spell upon biomechanics and BRV. Chapter Five presents the results from the third study which assessed the chronic effects of a periodised eight-week strength training program upon strength and the resulting implications upon FFC loading and BRV among fast bowlers. Chapter Six depicts the fourth study which ascertains the reliability and validity of IMUs for the determination of GRF during FFC. Chapter Seven contains a general summary and conclusion to the entire thesis. Studies one, two and three have all recently been submitted to the Journal of Sports Sciences for publication, while study four has been submitted to the Journal of Applied Biomechanics for publication.

At the request of the author,

Chapters 2, 3, 4, 5 and 6 are unavailable in this version of the thesis

CHAPTER SEVEN

General Summary and Conclusion

Summarises research findings and offers suggestions for future avenues of research

7.1 General Summary

The overall purpose of this thesis was to examine the acute effects of different delivery lengths upon fast bowling biomechanics and performance, as well as the possible chronic adaptations following a periodised strength training intervention. In addition, a preliminary investigation into the use of IMUs as a means of quantifying the biomechanics, and more specifically the loading, of the fast bowling action within match-play was presented. Previous research has investigated the biomechanics of the fast bowling action, but the majority of research has focused on the variables associated with BRV, with limited consideration to the possible implications of different delivery lengths.

Study one (Chapter Three) demonstrated that there were no significant differences in discrete or continuous biomechanical variables or BRV between short, good and full delivery lengths among fast bowlers. This was contrary to the study hypothesis and suggested that fast bowlers are able to utilise various delivery lengths without substantial changes in technique. Ultimately, this may be of benefit to fast bowling performance as significant changes in biomechanics may present as visual cues to a batsmen which would allow for greater decision making time, increasing the likelihood of successful stroke execution (Brenton et al., 2016). Practically, the lack of significant difference in GRF between the different delivery lengths provided justification for current bowling workload monitoring practices, which simply count the total number of deliveries, irrespective of delivery length (McNamara et al., in press; McNamara et al., 2015a; McNamara et al., 2017). Importantly, this is the first study to assess the implications of different delivery lengths upon commonly assessed biomechanical variables to BRV.

Study two (Chapter Four) investigated the implications of a match-specific eight-over bowling spell targeting different delivery lengths (short, good and full) upon selected fast bowling biomechanics and BRV. In-line with the studies hypothesis, the fast bowlers were able to maintain BRV throughout a single extended bowling spell. However, there was no change in discrete or continuous biomechanical variables. Fast bowlers were able to tolerate the repeated bouts of eccentric contractions associated with a single extended bowling spell. Practically, this study also provided support for current bowling workload monitoring practices in the applied setting (McNamara et al., in press; McNamara et al., 2015a; McNamara et al., 2017), by establishing that GRF during FFC did not significantly alter within a single eight-over spell.

Study three (Chapter Five) was the first study to conduct a periodised general strength training protocol to enhance BRV via attempting to optimise GRF during FFC. The results demonstrated that general resistance training can elicit significant improvements in lower-limb strength and eccentric capacity among fast bowlers. Although a significant increase in braking GRF for the full-length delivery at 4% of FFC normalised time was present, there were no other significant differences. This may explain why there was no significant change in BRV between pre- and post-testing, despite the improvements in strength and eccentric capacity. Nonetheless, this study provided valuable practical information about the strength profile of fast bowlers, as well as indicating that lower-limb eccentric capacity is a modifiable variable with appropriate training. Overall, study three may indicates that additional research is needed to determine what modifiable factors should be targeted to elicit changes in BRV among fast bowlers.

Study four (Chapter Six) provided a preliminary investigation into the usefulness of IMU derived trunk and tibia segment accelerations with respect to GRF during FFC. An accurate representation of GRF from the trunk and tibia segment accelerations, as compared to the criterion measure of an in-ground force plate, would have provided support for the use of IMUs to accurately quantify loading within match-play. However, the results outlined that trunk and tibia acceleration were a reliable, but not valid measure of GRF in the vertical or baking (horizontal) plane during FFC. With further investigation, segment acceleration could demonstrate significant relationships to performance variables associated with the fast bowling action, which could be collected within match-play and may prove to represent a relevant but unique measure of loading in comparison to GRF.

Collectively, these studies demonstrated that fast bowlers are able to target various delivery lengths with minimal changes to technique or BRV, either within a two- or eight-over bowling spell. Additionally, periodised general strength training can elicit significant improvements in strength and lower-limb eccentric capacity among fast bowlers. However, this does not appear to translate to changes in loading experienced at FFC or BRV. Lastly, segment acceleration does not appear to be an appropriate representation of GRF during FFC. Therefore, this thesis provided specific insight into the biomechanics and performance of the fast bowling action, with respect to different delivery lengths, strength training and the relevance of IMUs, which to date has received little or no attention within the scientific literature.

7.2 Directions for Future Research

Although many researchers have investigated the biomechanics of fast bowling, and this thesis has attempted to address gaps within the current literature, there are still avenues for further research in this area. Specific areas of interest for future research have been outlined within each of the previous studies. Nonetheless, key areas have been highlighted below:

- Future research should assess the relationship between segment acceleration and BRV. If a relationship between segment acceleration and BRV can be established, this may allow for pertinent biomechanical variables to be assessed during cricket match-play. This is particularly important when considering the physiological differences between match formats, and how this could affect fast bowling biomechanics and performance.
- Further investigation into the various applications of new technologies, such as IMUs, to the assessment of the fast bowling action is warranted. IMUs may be able to provide valuable information about key kinematic variables (i.e. lateral flexion, shoulder counter rotation or knee angle) of the fast bowling action within match-play.
- There needs to be an investigation of the effects of a combined strength and coaching intervention on the ability to alter key biomechanical variables and the resulting implications upon BRV should be determined. Results from the current study and

previous research indicated that strength and coaching interventions alone do not seem appropriate to elicit meaningful changes in performance. Accordingly, there should be analysis whether changes in strength, in conjunction with coaching of bowling technique, can elicit changes in BRV.

- The lack of significant improvement in lower-limb power measures following the eight week training intervention may highlight an area for future research. Specifically, future research which assesses whether a longer intervention period (i.e. greater than 12 weeks) which specifically targets lower-limb power should be undertaken to determine if there are any possible positive adaptations to BRV.
- The classification and analysis of fast bowlers based upon technique characteristics may provide new insight into the implications of an extended bowling spell upon fast bowling biomechanics. Specifically, when the fast bowlers utilised within study two were categorised based upon knee kinematics between FFC and ball release as per Portus et al. (2004), the constant brace group (n = 3) reported a 6% (effect size [*d*] = 4.05) increase in peak vertical GRF between the mean pooled delivery lengths from the initial and last three overs of an eight-over spell. Practically, this could have implications upon bowling workload monitoring and strength and conditioning practices. However, it is important to note that such methods reduce the statistical power of the findings and also limited the application of the findings to a wider population of fast bowlers.
- To date, there has been a paucity of research which has investigated the biomechanics and performance of female fast bowlers. Studies one to three could be reproduced with female fast bowlers to determine whether changes in delivery length result in

biomechanical and performance alterations, as well as the implications of a strength training intervention. This would provide much needed insight into the biomechanics of the fast bowling action for females.

- Due to the high prevalence of change of pace deliveries within the shorter match formats, future research shoulder determine the biomechanical implications associated with change of pace deliveries in comparison to standard deliveries for fast bowlers.

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APPENDIX A

Proof of Ethics

To:Samuel CALLAGHAN <scallag5@our.ecu.edu.au>;

Cc:Research Assessments <researchassessments@ecu.edu.au>; Sophia NIMPHIUS <s.nimphius@ecu.edu.au>; FHES Student Information Office <siofhes@ecu.edu.au>;

1 attachments (47 KB)

Conditions of approval.pdf;

Hi Samuel

Project Number: 11948 CALLAGHAN
Project Name: The Mechanics of Front Leg Loading During Cricket Fast Bowling: Delivery Variations, Spell Demands, and the Effect of Strength Training

Student Number: 10356859

The ECU Human Research Ethics Committee (HREC) has reviewed your application and has granted ethics approval for your research project. In granting approval, the HREC has determined that the research project meets the requirements of the *National Statement on Ethical Conduct in Human Research*.

The approval period is from 2 March 2015 to 6 March 2017.

The Research Assessments Team has been informed and they will issue formal notification of approval. Please note that the submission and approval of your research proposal is a separate process to obtaining ethics approval and that no recruitment of participants and/or data collection can commence until formal notification of both ethics approval and approval of your research proposal has been received.

All research projects are approved subject to general conditions of approval. Please see the attached document for details of these conditions, which include monitoring requirements, changes to the project and extension of ethics approval.

Please feel free to contact me if you require any further information.

Kind regards

Rowe

Rowe Oakes
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