Objective Analysis of Cricket Fast Bowling Intensity

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Statement of Authorship

I, Daniel Epifano, declare that except where reference is made in the text of the thesis, this thesis entitled "Objective Analysis of Cricket Fast Bowling Intensity" contains no material published elsewhere or extracted in whole or in part from a thesis accepted for the award of any other degree or diploma. No other person's work has been used without due acknowledgment in the main text of the thesis. This thesis has not been submitted for the award of any degree or diploma in any other tertiary institution.

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Abstract

The ability to monitor fast bowling activity in cricket is important for coaches and practitioners, due to the considerable rate of non-contact injuries among fast bowlers. The concurrent use of trunk-GNSS (global navigation satellite system) and tibial-IMU (inertial measurement unit) devices could enable objective measurement of fast bowling delivery intensity in outdoor cricket settings.

A literature review discussed recent methods of fast bowling delivery intensity measurement, which have relied solely on trunk-mounted devices during outdoor assessment. Trunk-worn devices cannot accurately measure the kinematics of the lower limbs, where a large portion of fast bowler injury occurs. This thesis aimed to investigate the utility of trunk-GNSS and tibial-IMU devices to estimate fast bowling delivery intensity, and to compare peak acceleration measures across delivery and follow-through foot strikes to infer changes in tibial load.

Fifteen sub-elite fast bowlers (mean ± SD; age 21.0 ± 3.8 years) performed deliveries at perceived warm-up, match and maximal intensities while wearing a trunk-GNSS unit, and tibial-IMUs on either leg. This thesis showed that:

1) Trunk and tibial device measures are distinguishable between warm-up to perceived match and maximal intensity deliveries.
2) The greatest magnitude of tibial acceleration is at the back foot re-contact strike.
3) Delivery and follow-through foot strikes represent unique aspects of the lower-limb load in fast bowling.
4) The magnitude of tibial acceleration at front-foot re-contact is not significantly different from the initial front-foot contact.

This thesis demonstrates a utility of trunk-GNSS and tibial-IMU measures to determine kinematic changes relative to bowling intensity. Considerable magnitudes of tibial acceleration at the follow-through foot strikes present a novel finding in current fast bowling research. Further research is required to understand the significance of those accelerations force loads, their contribution to delivery intensity, and potential involvement in injury development.

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List of Abbreviations

BF1	Initial back-foot contact (delivery stride)
BF2	Back foot re-contact (follow-through stride)
FF1	Initial front-foot contact (delivery stride)
FF2	Front-foot re-contact (follow-through stride)
GNSS	Global Navigation Satellite System
GRF	Ground reaction force
IMU	Inertial Measurement Unit
PCA	Principal Component Analysis
RPE	Rate of perceived exertion
TFV	Trunk flexion velocity
TLV	Trunk lateral flexion velocity
TRV	Trunk rotation velocity
T20	Twenty-over innings cricket match

Chapter One

Introduction

1.1 Background

Cricket is a non-contact team sport that involves specialised skills associated with playing positions of batting, bowling, and fielding. Each role on the field requires a specific level of intensity, athleticism, and training regime to be performed effectively, with players typically expected to excel in at least one role to be deemed worthy of team selection. Balls in cricket are grouped in 'overs' consisting of six fair deliveries. Bowlers are rotated at the completion of the over and the next over begins from the opposite end of the pitch. Cricket matches are played in one of two formats: limited overs, or multi-day (two innings per team). At the professional level, limited over matches are typically One-Day (50-overs per innings) or T20 (20-overs per innings), while multi-day matches can continue for up to five days before a result.

Fast bowlers report the greatest injury incidence of all cricketers (Davies et al., 2008; Hulin et al., 2014; Portus et al., 2004; Soomro et al., 2018). Injuries to fast bowlers typically occur in the lower limbs and low back, often consisting of joint sprains, muscle strains, and bone stress fractures (Davies et al., 2008; Orchard et al., 2015). Low-back injuries make up 37-55% of all injuries among junior bowlers (Davies et al., 2008), 40% in adult fast bowlers (Mansingh et al., 2006), and account for the longest periods of lost playing time among professional cricketers (Newman, 2003; Orchard et al., 2006). Lumbar stress fractures can also be asymptomatic for several weeks, placing athletes at risk of further injury with continued training (Crewe et al., 2012; Ranson et al., 2010). Such is the risk of undetected injury, cricket councils have begun implementing training restrictions on fast bowlers, particularly at the junior levels (Cricket Australia, 2019). The frequency and severity of fast bowling injuries have meant fast bowlers miss about 16% of total playing time, whilst cricketers from all other positions combine for less than 5% of playing time missed (Orchard et al., 2006). Three commonly identified fast bowling actions include side-on, front-on and mixed, which describe the alignment of the hip and shoulders through the delivery stride (BF1) (Bartlett et al., 1996; Elliott et al., 1992; Portus et al., 2004). Whilst some of the injury causation in fast bowling can be linked to poor technique (Alway et al., 2021; Bartlett et al., 2017) and bowling action type (Bartlett et al., 1996; Portus et al., 2004), the stress-induced, non-contact nature of fast bowling injuries suggests that bowling volumes and intensities are associated with injury incidence (Hulin et al., 2014). Hence, an understanding of these factors is imperative to manage injury risk and inform coaches for evidence-based training programming.

Athlete activity monitoring is pervasive in team field sports (Cummins et al., 2013). Namely, trunk-worn global navigation satellite system (GNSS) units (which often also house accelerometer and gyroscope sensors) are commonly used to assess athlete external loads via total distance covered and changes in acceleration (Cummins et al., 2013). GNSS-unit data can be utilised by coaches and practitioners to identify different periods of intensity during training and match-play (Gabbett et al., 2017). Research in cricket has demonstrated a utility of GNSS unit data, in differentiating the external loads of athletes from different playing positions (Petersen et al., 2010). Fast bowlers complete the greatest overall volumes of activity and time under high exertion, relative to all other cricketing positions (Hulin et al., 2014; Orchard et al., 2009). The most physically demanding task for the fast bowler is the act of fast bowling. The fast bowling routine involves a run-up of self-selected length; a pre-delivery stride, involving a forward leap as the bowler approaches the popping crease in preparation for the delivery stride; the delivery stride, where the bowler transfers linear momentum from the lower to upper-limbs whilst rotating the trunk to generate a faster ball release; and the follow-through, where the bowler decelerates and regains balance after ball release (Bartlett et al., 1996). High-speed run-ups that culminate into rapid trunk accelerations and large ground reaction forces (GRFs) at front foot contact, are the particularly demanding elements of the fast bowling action (Ranson et al., 2008; Worthington et al., 2013a). Biomechanical assessments of fast bowlers are typically made using force platform measurement (Worthington et al., 2013a) and three-dimensional motion analysis (Ranson et al., 2008; Worthington et al., 2013a) in laboratory settings. However, the accessibility and functionality of such assessment methods are limited in the outdoor training environment, based on the high cost and limited flexibility of those instruments.

Recent research has established a more field-compatible measure of fast bowling intensity using wearable microtechnology (McNamara et al., 2018), however, this method is not finalised. In an examination of twelve elite fast bowlers, McNamara et al. (2018) adopted GNSS units to estimate trunk angular velocities, acceleration, PlayerLoad™, and ball speed and perceived exertion to determine the utility of those metrics to classify bowling intensity. The research found large relationships between trunk-device outputs, prescribed intensity, and ball speed, demonstrating an effectiveness of microtechnology in objectively classifying fast bowling intensity (McNamara et al., 2018). Whilst this method of delivery intensity classification is reliable (McNamara et al., 2018), trunk-mounted devices do not account for the kinematics of the lower limbs (Panther & Bradshaw, 2013), where a large portion of injuries in fast bowling are known to occur (Davies et al., 2008).

The delivery stride is currently accepted as the most physically impactful phase of the fast-bowling routine (Bartlett et al., 1996; Portus et al., 2004; Ranson et al., 2008; Worthington et al., 2013a). During the delivery stride, fast bowlers perform vigorous trunk and upper-limb rotations (Bartlett et al., 1996), before experiencing large GRFs of up to eight times their body weight at front-foot contact (FF1) (Bartlett et al., 1996; Portus et al., 2004; Ranson et al., 2008; Worthington et al., 2013a). GRFs absorbed at FF1, combined with the precarious upper-body kinematics, are believed to place considerable stress on the lumbar spine, contributing to the injury risk at the low back (Alway et al., 2021). Laboratory testing has adopted force platform measurements to measure GRFs at FF1 (Callaghan et al., 2021; Worthington et al., 2013a). However, perhaps due to a performance-based research rationale in fast bowling, which has focused on GRFs prior to ball release (Ranson et al., 2008; Worthington et al., 2013a), the GRFs at the follow-through strikes have remained unassessed. Technique and injury based analyses in other sports, like in baseball pitching and golf swinging, have demonstrated rapid deceleration and subsequent force development in the follow-through phases of either activity (Pappas et al., 1985; Steele et al., 2018). The large deceleration forces in those activities place considerable strain on the active joints and musculature, linking the braking forces at the follow-through to onset of injury at these sites (Pappas et al., 1985; Steele et al., 2018). Peak braking (deceleration) forces have also been linked to the development of tibial stress fractures in runners (Napier et al., 2018). Given the considerable linear acceleration of the fast bowling run-up phase, and consequently large force magnitude reported at the front foot strike of the delivery stride (Worthington et al., 2013a), it is plausible to assume a similar (if not greater) force production in the follow-through foot strikes, as the bowler rapidly decelerates. It would therefore also be possible that the kinetics of the follow-through contribute to injury onset in fast bowlers, as is hypothesised of the delivery stride foot strikes (Alway et al., 2021; Worthington et al., 2013a). To date, however, no research is currently available that reports lower-limb contact forces in the fast bowling follow-through.

Tibial inertial measurement units (IMUs) provide valid and reliable tibial acceleration measurement in running gait analysis (Norris et al., 2014), and can provide contextual information on injury-inducing leg kinematics (Murai et al., 2018). Tibial-IMU devices have been utilised in research to infer GRF and tibial load in impactful lower-extremity activities such as gymnastics and running (Campbell et al., 2020; Tenforde et al., 2020). Recently, tibial-IMUs have been adopted in fast bowling research, reporting a positive correlation between IMU-derived force signatures and GRF measures from a force platform (Callaghan et al., 2020). Whilst tibial-IMUs cannot report reaction forces to the accuracy of a force platform, changes in tibial acceleration between bowling foot strikes could be indicative of tibial load differences (Callaghan et al., 2020). Tibial-IMUs could therefore be adopted to compare lower-limb kinematics and infer changes in tibial load across the fast bowling delivery, in outdoor cricketing environments. Such information could also provide context behind injury development.

1.2 Statement of the Problem

Current methods of fast bowling intensity assessment rely on trunk-worn devices and ball speed measures to infer intensity and detect individual deliveries (Jowitt et al., 2020; McNamara et al., 2018). Although strong relationships are evident between trunk angular velocities, PlayerLoad™, ball speed, and prescribed intensity, these measures are only representative of the physical exertion of the trunk, and do not represent the external demands of the lower limbs (Callaghan et al., 2020). Whilst lower-limb loads have been assessed via force platform measurement (Callaghan et al., 2021; Worthington et al., 2013a), the financial cost and laboratory-based nature of this method limit its practicality in outdoor training settings. Additionally, kinematics of follow-through foot strikes in fast bowling have not been assessed. Research in other sports suggests a potential link between repeated decelerations in the follow-through phase and subsequent onset of stress injury (Pappas et al., 1985; Steele et al., 2018). This may also be apparent for the fast bowling delivery in cricket, where considerable volumes of stress-related injuries are observed (Davies et al., 2008; Hulin et al., 2014; Orchard et al., 2015).

1.3 Aims and Hypothesis

By adopting a global focus towards fast bowling analysis (irrespective of bowling technique variations), this thesis pursued the following aims:

- To review the current literature on methods for measuring fast bowling intensity.
- To investigate the utility of metrics derived from wearable trunk- and tibia-mounted microtechnology devices, together with common external bowling intensity measures, to objectively quantify fast bowling delivery intensity.
- To compare peak resultant tibial accelerations across the delivery and follow-through foot strikes.
- To investigate potential relationships between foot strike accelerations, trunk-metrics, ball speed and rate of perceived exertion across prescribed bowling intensities

It was hypothesised that a relationship between resultant tibial accelerations, trunk and external intensity outputs, and prescribed intensity would be observed and that the follow-through strikes of the fast bowling delivery would also record large tibial accelerations.

1.4 Significance of this Thesis

The ability to assess tibial kinematics using tibial-IMU measurements could facilitate a new method of lower-limb intensity assessment in fast bowling that is applicable to the outdoor training setting. An assessment of the delivery and follow-through foot strikes may reveal valuable information regarding the kinematics of the follow-through, perhaps uncovering a novel component of fast bowling intensity that warrants further attention concerning injury-risk reduction. Furthermore, this thesis demonstrates an ability to objectively measure fast bowling intensity in the typical training environment. This could, therefore, contribute to the directions of future research, which may eventually develop competition-based methods of fast bowling intensity quantification, building upon on the training quantification procedure established in this thesis. Ultimately, findings from this thesis may convey the capabilities of trunk and tibia-mounted devices in the objective assessment of fast bowling delivery intensity within the outdoor training setting.

1.5 Delimitations

This thesis focuses on the biomechanical assessment of cricket fast bowling via use of wearable microtechnology. The authors acknowledge that variations in bowling technique are often observed among fast bowling cohorts. Whilst technique can be an important factor in coaches' skill development of athletes, variations in bowling action (i.e. front-on/side-on/mixed) were not analysed. Thus, to remove any potential between-participant effects of technique, bowling data in Chapter 3 was converted to individual percentage-maximum scores before analysis, whilst Chapter 4 followed a within-participant analysis method.

Chapter Two

Literature Review

2.1 Introduction

Cricket bowling consists of varying approaches in technique and intensity, depending on the bowling style. There are three main bowling styles, including spin, medium-pace, and fast bowling. A spin bowler will typically endeavour to bowl slow deliveries that drift during flight and deviate after bouncing to deceive the batter, whereas a pace (medium/fast) bowler will aim to beat the batter with ball speed, bounce, and swing. Fast bowling is accepted as the most physically strenuous activity in cricket, underlined by the greater injury rates in fast bowlers compared with other cricketers (Davies et al., 2008; Hulin et al., 2014; Orchard et al., 2006). Whilst some research has linked technique deficiencies to injury occurrence (Portus et al., 2004; Worthington et al., 2013a), excessive fast bowling volumes are believed to be largely responsible for the onset of injury (Davies et al., 2008; Hulin et al., 2014; Orchard et al., 2009). Such is the established link between bowling volume and injury in fast bowlers, restrictions on training are being implemented from as early as the junior domestic levels (Cricket Australia, 2019; Schaefer et al., 2018). Injuries sustained throughout a fast bowler's cricketing career can have implications for their competitive aspirations and in some cases, long-term effects on their physical wellbeing in retirement from the sport (Bali et al., 2011; Debnath et al., 2007).

Research has objectively demonstrated more physically demanding bouts of activity among fast bowlers compared to other cricketing positions based on larger quantities of sprint efforts with considerably smaller work-to-rest ratios (Petersen et al., 2010). Additionally, fast bowlers are known undergo considerably large ground reaction forces (GRFs) at front foot contact, a by-product of faster run-up speeds in comparison to slow/spin bowlers (Worthington et al., 2013a). More recently, research has sought to quantify fast bowling intensity using wearable microtechnology data, enabling objective measurement of fast bowling effort during training (McNamara et al., 2018). However, current bowling intensity-monitoring methods do not account for the activity of the lower limbs, despite the considerable GRF loads experienced in the lower-limbs (Worthington et al., 2013a). Hence, an objective measure of fast bowling intensity that considers the trunk and lower limbs is required, to provide coaches and practitioners the ability to accurately monitor the physical exertion levels of fast bowlers. This literature review will present current injury incidence in cricket, report physical demands and monitoring practices of fast bowlers, and discuss methods of quantifying fast bowling delivery intensity

2.2 Injury in Cricket

Cricketers are exposed to substantial injury risk from impacts, slips/falls, and repetition/overuse, resulting from poor technique and/or conditioning (Orchard et al., 2015; Portus et al., 2004; Walker et al., 2010). Most injury incidences reported in cricket occur during bowling, followed by fielding, batting, and wicket-keeping activities (Orchard et al., 2006; Pardiwala et al., 2018; Walker et al., 2010). Commonly injured body regions include the upper and lower limbs, followed by the low back, then the trunk/back, head, and neck (Orchard et al., 2006; Pardiwala et al., 2018; Walker et al., 2010). Whilst recognition and use of player conditioning, activity assessment technology, and protective equipment have all become more common since the turn of the century, injury rates across elite cricketers have remained stable (Pardiwala et al., 2018; Soomro et al., 2018). The introduction of twenty-over (T20) competitions over the past two decades are also speculated to have increased the amount of overuse injuries, due to congested match-scheduling and lack of an off-season for many cricketers. However, research is yet to find a significant correlation between T20 schedules and overuse injury (Orchard et al., 2015; Soomro et al., 2018). The uncertainty surrounding the prevalence of non-contact overuse injury in cricket provides a challenging opportunity for researchers to delve into the aetiology of overuse injury in fast bowlers.

Fast bowlers have the greatest injury occurrence of all cricketers (Davies et al., 2008; Hulin et al., 2014; Portus et al., 2004; Soomro et al., 2018). The mechanisms behind injury onset are multifactorial, and include an extrinsic factor in bowling volume (Davies et al., 2008; Hulin et al., 2014; Olivier et al., 2016; Orchard et al., 2009) and intrinsic factors such as age, conditioning level, injury history, and bowling technique (Blanch et al., 2015; Olivier et al., 2016). Not only is the incidence of injury in cricket fast bowlers more prevalent than other positions, but is also more severe – as fast bowlers typically miss around one in every seven matches through injury (Davies et al., 2008; Orchard et al., 2006). Injury incidence relative to athletic exposure hours in junior and amateur cricketers (129.7/10,000 hours) is also higher than in sportspeople of comparable age and competition level playing in non-contact or quasi-contact sports such as soccer (35.4/10,000 hours), basketball (33.19/10,000 hours) and tennis (40.2/10,000 hours) (Soomro et al., 2018). Large GRFs and rapid trunk angular accelerations (Portus et al., 2004; Worthington et al., 2013a), coupled with repeated delivery efforts and bowling volumes (Davies et al., 2008; Hulin et al., 2014; Orchard et al., 2009), appear to be the predominant causes of lower-back injury in fast bowling. This is a particular issue for junior fast bowlers who are more susceptible to lumbar stress fractures, due in part to the immaturity of the lumbar spine through adolescence (Crewe et al., 2012). One study found that lower-back injuries reportedly make up 37-55% of all injuries in junior cricket fast bowlers (Davies et al., 2008), whilst research in the West Indies found that 40% of injuries in adult fast bowlers occurred at the lumbar spine (Mansingh et al., 2006). Furthermore, research has reported that, in many cases, lumbar spine stress injury is asymptomatic and can occur before the onset of pain, increasing the risk of further injury (Crewe et al., 2012).

The frequency and severity of fast bowling injuries have meant fast bowlers miss about 16% of matches, whilst cricketers from all other positions combine for less than 5% of matches missed through injury (Orchard et al., 2006). Such knowledge has encouraged the Australian national cricket body (Cricket Australia) to place training and match restrictions on the number of deliveries junior players can bowl within given timeframes (Cricket Australia, 2019). Whilst ball counting has been used for basic activity tracking assessment (Hulin et al., 2014), this method only provides a gross measure of the total delivery volume, lacking contextual information about the delivery intensity. Fast bowling monitoring methods that incorporate qualitative and quantitative physical exertion data would enhance current knowledge behind tailored athlete conditioning. This descriptive information would assist coaches in prescribing individualised session intensity levels – possibly through prescribed rest periods – to alleviate the risk of injury.

2.3 The Physical Demands of Fast Bowling

Fast bowlers have a greater overall level of activity and exertion compared to other cricketing positions (Hulin et al., 2014; Orchard et al., 2009). In a study of cricket players from five different positions – batting, fast-bowling, spin bowling, wicketkeeping, and fielding – fast bowlers reportedly sprinted twice as often and covered over three times the distance sprinting, with much smaller work-to-rest ratios than the other positions (Petersen et al., 2010). Across all positions, T20 is the most intensive match format per unit of time (Bliss et al., 2021), while Test Matches report greater overall volumes of activity, due to being completed over multiple days (Petersen et al., 2010). Fast-bowlers are also required to produce intense, high-velocity actions throughout their bowling routines, including trunk extension, lateral flexion, rotation, and shoulder flexion (Bartlett et al., 1996). During the delivery stride, fast bowlers produce these rapid trunk movements while also enduring GRFs of up to eight times their body weight (Portus et al., 2004). During a multi-day match where bowling volumes are unrestricted, fast bowlers could experience those stressful body movements and large GRFs over 300 times (Orchard et al., 2009). This is problematic for fast bowlers, as a considerable link between GRFs and lumbar stress fractures has been hypothesised (Alway et al., 2021; Worthington et al., 2013a).

Research has sought to examine the relationship between bowling volume and associated injury risks in fast bowlers (Davies et al., 2008; Hulin et al., 2014; Orchard et al., 2015). A negative training-stress balance (where a player may be overtraining and has a high acute load in comparison to their chronic training load) has been linked to greater injury susceptibility (Hulin et al., 2014). There also appears to be a positive relationship between high acute match volume (≥50 overs) and high previous season volume (≥400 overs) on subsequent injury risk (Orchard et al., 2015). Furthermore, for bone stress injuries, high medium-term (≥150 overs in 3-months), and low career volume (<1200 overs) are also risk factors for injury in first-class fast bowlers (Orchard et al., 2015). Interestingly, when the acute volume is modest, high previous season volume is found to have a slight protective effect on injury risk (Orchard et al., 2015). These findings highlight the importance of periodisation of training volume, with adequate recovery periods needed between bouts of substantial activity, both within- and between-seasons. This is particularly the case for junior athletes who are at greater risk due to their developmental stage (Davies et al., 2008). While quantification of general activity volume is important, a method of fast bowling analysis that considers delivery intensity and frequency in addition to volume could provide greater information to appropriately inform the design of periodised training programs for individual fast bowlers.

2.4 Activity Monitoring and Measurement

The ability to accurately measure physical activity is a crucial element in the assessment of athlete intensity throughout match-play, training, and competition seasons. Research surrounding the application of activity monitoring is growing (Bourdon et al., 2017;

Cummins et al., 2013), particularly in team sports where athletes are regularly performing in longer competition seasons spanning several months. In team sports, activity load monitoring can consist of internal load measures, such as heart rate and rating of perceived exertion (RPE); and 'external' measures, i.e. via global navigation satellite system (GNSS) and accelerometry devices, or repetition counts, and training duration (Bourdon et al., 2017; Cummins et al., 2013). A combination of these internal and external metrics provide practitioners information regarding the magnitude of athletes' session intensity, their response and tolerance of that session, and assists in the decision making process regarding readiness for subsequent training and the content of those sessions (Gabbett et al., 2017). Nowadays, most elite sports incorporate wearable technology (such as GNSS or accelerometers) to measure physical demands (Sperlich et al., 2019).

In recent times, trunk-GNSS units have become more pervasive in team field sports (Cummins et al., 2013). Housing a GNSS receiver, an accelerometer, a magnetometer and a gyroscope, the GNSS unit positioned on an athlete's upper back can be used to assess external load via total distance covered and changes in acceleration (Bliss et al., 2021; Cummins et al., 2013). This information serves as a means of player activity monitoring in training and competition to identify highly-intense periods (Cummins et al., 2013). Whilst the application of trunk-GNSS is decidedly more prevalent in team sports involving continuous running efforts – such as Australian Football, soccer, and hockey (Cummins et al., 2013) – some use of the unit has also been adopted in cricket. Trunk-GNSS has been used in cricket to detect movement patterns of field players (Bliss et al., 2021; Petersen et al., 2010) and, more recently, researchers have begun to employ GNSS to automatically detect fast-bowling activity (Jowitt et al., 2020; McNamara et al., 2015a). Whilst GNSS data can contribute to the understanding of a fast-bowler's overall activity volume, the accelerometer, magnetometer and gyroscope devices encompassed in the trunk-worn unit cannot adequately measure the activity of the distal body segments, such as the upper- and lower limbs (Panther & Bradshaw, 2013). To accurately estimate movements peripheral to the trunk, segment-based devices are required. This is particularly relevant for high-intensity running activities including fast bowling, which has shown to elicit considerable tibial loads and GRFs during the delivery stride (Portus et al., 2004).

Inertial measurement units (IMUs) facilitate measures of acceleration, allowing for inferences of force and segment loads during activity (Campbell et al., 2020; Tenforde et al., 2020). Like the GNSS unit, IMUs house a collection of sensors, including a triaxial accelerometer, gyroscope, and magnetometer to measure linear acceleration and angular velocity of movements. Given their size and portability, IMUs allow for a more localised measurement of acceleration and angular velocity, as they can be attached to any segment. A systematic review of studies that have incorporated the use of tibia-mounted IMUs validated their use for measuring tibial acceleration and shock absorption during running gait (Norris et al., 2014). Comparatively, trunk-mounted IMUs (similar to GNSS units) do not provide accurate and reliable readings of limb acceleration or GRF data (Callaghan et al., 2020; Panther & Bradshaw, 2013). Given the multi-segment nature of the fast bowling action (Bartlett et al., 1996; Orchard et al., 2009; Petersen et al., 2010; Portus et al., 2004; Worthington et al., 2013a), segment-based accelerometry (such as tibial-mounted IMUs) may help to improve coaches' understanding and subsequent prescription of training and match loads. Laboratory-based fast bowling research has assessed distal-segment kinematics using IMUs (Callaghan et al., 2020), although this method of distal-segment assessment is yet to be applied in outdoor cricketing settings.

When measuring the activity demands of fast bowling, research typically focuses on the upper and lower body loads during the delivery stride. The delivery stride is a precarious phase of the fast bowling delivery, given the rotated position of the spine coinciding with a spike in GRF at front-foot contact (Bartlett et al., 1996; Worthington et al., 2013a). The coupling of spine rotation and peak GRF events has been linked to the onset of lumbar stress injuries among fast bowlers (Zhang et al., 2016). Whilst delivery stride is of particular research interest, no previous fast bowling research has investigated the biomechanics of the follow-through. Previous studies in golf and baseball have highlighted the follow-through period as an important aspect of those techniques, based on linked injury consequences (Pappas et al., 1985; Steele et al., 2018). The follow-through period in golf and baseball involves rapid decelerations that results in considerable strain on the active joints and musculature (Pappas et al., 1985; Steele et al., 2018). Given the explosive nature of the fast-bowling delivery, involving a considerable development of linear acceleration in the run-up phase (Bartlett et al., 1996; Worthington et al., 2013a), it is possible that bowlers undergo a similar pattern of stress in the deceleration of their follow-through. Decelerations would presumably peak at the ground re-contacts after ball release, as the bowler seeks to maintain balance.

2.5 Quantifying Fast Bowling Delivery Intensity

Current methods of objective fast-bowling delivery intensity quantification typically involve recordings of ball speed and PlayerLoad™ (a metric derived from GNSS units) (McNamara et al., 2018). Whilst the absolute measure of ball speed reflects an aspect of delivery performance, it does not account for individual differences in technique or ability between bowlers, and therefore cannot be used as a sole global intensity measure. PlayerLoad™ (calculated by the square root of the sum of the squared instantaneous rate of change in acceleration in each of the three vectors, divided by 100) is a popular metric for assessment of session and activity intensity in team sports, particularly Australian Football (Boyd et al., 2013). Research in Australian football has demonstrated the application of PlayerLoad™ as an intensity estimate, by using PlayerLoad™ measures to differentiate external loads between playing positions (Boyd et al., 2013). Similar applications of PlayerLoad™ have been utilised in cricket, to estimate fast bowling delivery intensity (McNamara et al., 2015b). PlayerLoad™ was found to be a 'stable' measure that changed in accordance with relative ball speed (McNamara et al 2015b). More recently, PlayerLoad™ has been shown to have a very large relationship to both ball speed and prescribed intensity across four prescribed intensity levels (McNamara et al., 2018). While a plateau in ball speed occurred at the higher levels of prescribed effort, PlayerLoad™ was still able to differentiate between the higher bowling intensities (McNamara et al., 2018). However, a high coefficient of variation for PlayerLoad™, made it difficult to accurately classify bowling intensity using PlayerLoad™ alone (McNamara et al., 2018). Therefore, PlayerLoad™ appears to be a suitable measure of fast bowling delivery intensity compared to ball speed, although additional measures may be required to provide a more accurate, gross assessment of delivery intensity.

Whilst some evidence supports the utility of trunk devices to objectively quantify fast bowling delivery intensity (McNamara et al., 2018), trunk-worn devices cannot account for kinematics of the lower limbs (Panther & Bradshaw, 2013). Lower-limb assessment is a critical aspect of objective fast bowling intensity measurement, based on the large portion of fast bowler injury reported in the lower limbs (Davies et al., 2008). Previous fast bowling research has utilised force platforms and three-dimensional motion analysis to assess lower-limb biomechanics (Callaghan et al., 2020; Worthington et al., 2013a), however, these methods have limited practicality in the outdoor training environment. Tibial IMUs could enable proxy measurement of lower-limb loading in outdoor environments. Peak resultant tibial acceleration derived from tibial-IMU has recently been reported as a surrogate measure of leg loading in gymnastics (Campbell et al., 2020) and running (Tenforde et al., 2020). Using Newton's second law of motion; *force* = *mass* × *acceleration*, changes in IMU-acceleration at the limb can infer external loads on exact body segments (Campbell et al., 2020; Tenforde et al., 2020). Fast bowling research has reported that estimates of GRF cannot be accurately attained from trunk- or tibia-IMUs, yet there is an acceptable level of error and a positive correlation between tibial-IMU force signatures and discrete GRF measures (Callaghan et al., 2020). However, research in fast bowling is yet to adopt tibial-IMU as a field-based means of force estimation. Involvement of tibial-IMU in fast bowling delivery assessment could facilitate the objective measurement of lower-limb intensity. The wearable device could be used to estimate tibial loads at foot-strikes across the entire delivery, including the follow-through where tibial loads remain unassessed. The inclusion of tibial acceleration as an additional measure may contribute to a greater understanding of intensity and more detailed assessment of bowling activity.

2.6 Conclusion

Cricket fast bowlers are more susceptible to injury than all other positions in cricket (Davies et al., 2008; Hulin et al., 2014; Orchard et al., 2006). Namely, cricket fast bowlers predominantly suffer higher rates of lower body strains and low back stress fractures compared to other positions, particularly in the junior level (Crewe et al., 2012; Davies et al., 2008). Potential links between forces through the lower limb and lumbar stress have been hypothesised as one of the main causes for this greater injury rate (Bartlett et al., 1996; Worthington et al., 2013a). Injury incidence and consequent incapacity rates are of great concern for fast bowlers, who typically undergo longer rehabilitation periods than their peers (Orchard et al., 2006). Whilst a portion of the fast-bowling injury aetiology could be linked to improper technique (Portus et al., 2004), current research suggests excessive bowling volumes and intensity are the predominant causes of injury incidence (Hulin et al., 2014; Orchard et al., 2015; Orchard et al., 2009).

In recent years, methods to monitor fast bowling intensity have become more prevalent (McNamara et al., 2018; McNamara et al., 2015b). Whilst research has identified reliable bowling intensity metrics (McNamara et al., 2015b), a method of objective fast bowling intensity classification that includes assessment of the lower limbs in the outdoor training environment, has yet been established. Tibial-IMUs have been successfully implemented in other high-impact, lower-extremity activity research, where tibial accelerations provided reliable force-surrogate measures (Campbell et al., 2020; Tenforde et al., 2020). Whilst tibial-IMUs cannot be used to estimate GRF magnitudes to the accuracy of force platforms, acceleration measures from tibial-IMUs represent an acceptable level of error and could therefore represent changes in tibial load (Callaghan et al., 2020). A further investigation into the contribution of the lower limbs to the physical demand of the bowling delivery, may provide a more accurate assessment of whole-body fast bowling intensity. Additional knowledge in this space could have implications for training management and injury prevention.

Chapter Three

Objective assessment of fast bowling delivery intensity in amateur male cricketers

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3.1 Abstract

Wearable microtechnology is effective in detecting fast deliveries in cricket, however, methods to quantify delivery intensity have not been established. This study aimed to investigate the utility of wearable sensors in quantifying cricket fast bowling intensity. Fifteen sub-elite male fast bowlers performed deliveries at warm-up, match, and maximal intensities. A principal component analysis resulted in the selection of perceived exertion and seven variables of bowling exertion derived from trunk- (PlayerLoad™, trunk flexion velocity, trunk forward rotation velocity) and tibia-mounted (tibial acceleration at back foot contact, front foot contact, back foot re-contact and front foot re-contact) inertial measurement units for further analysis. Repeated measures ANOVAs were used to investigate the effect of intensity on outcome variables. Significant main effects of intensity and large effect sizes were identified for all variables ($p < .05$, $n^2_p > 0.14$). Measures from the match and maximal conditions were significantly larger compared with the warm-up condition ($P_{holm} < .05$). No differences were observed between the match and maximal conditions ($p > .05$). Inertial measurement metrics can distinguish between a warm-up effort and both match and maximal fast bowling delivery intensity. These devices provide a unique, time-efficient approach to cricket fast bowling exertion quantification.

Keywords: intensity, classification, tibial acceleration, microsensors, training

3.2 Introduction

Innovations in activity-monitoring technology, particularly wearable global navigation satellite system (GNSS) devices, have allowed the assessment of training and match demands in team sports to become more automated (Jowitt et al., 2020) and individualised (Bartlett et al., 2017). An individualised approach to training is essential in cricket, as different match formats and positional roles can require considerably different physical loads (Bliss et al., 2021; Petersen et al., 2010) and susceptibility to injuries (Orchard et al., 2015). This is particularly evident among fast bowlers, who are most at-risk to injury of all cricketers (Orchard et al., 2015). Whilst research has shown associations between fast bowler injuries and technical factors (Alway et al., 2021; Bartlett et al., 2017), excessive bowling volume has also been linked to fast bowler injury (Hulin et al., 2014), particularly at the lumbar spine (Alway et al., 2021; Davies et al., 2008; Orchard et al., 2015). Bowling volume has historically been measured as ball counts recorded with pen and paper, however, advances in technology have led to the use of microsensors and machine learning for this purpose (Hulin et al., 2014; Jowitt et al., 2020; McGrath et al., 2021; McNamara et al., 2015a) and more recently, to estimate bowling intensity (McGrath et al., 2021). Whilst there is ample research into the physical demands of fast bowling based on volume of deliveries, the quantification of intensity for monitoring purposes is scarce. Therefore, the utility of more advanced technologies to objectively measure bowling intensity is still relatively unknown.

Wearable GNSS devices have been utilised in numerous activity-monitoring studies (Bourdon et al., 2017; Sperlich et al., 2019), and are used by practitioners in team sports to individualise activity data, due to the functionality of real-time reporting (McNamara et al., 2018; McNamara et al., 2015a). Recent efforts have been made to measure the intensity of deliveries from cricket fast bowlers using trunk-worn GNSS units with embedded inertial measurement units (IMUs) (Jowitt et al., 2020; McNamara et al., 2018). These devices provide a range of locomotive and inertial movement data that provide information on training intensity variables, such as the IMU-derived PlayerLoad™. PlayerLoad™ is a proprietary measure, calculated using the accelerometer within the IMU, and is a valid metric when measuring bowling intensity in fast bowling (McNamara et al., 2018). Additionally, the gyroscope within IMUs provide rotational measures around the roll, pitch, and yaw axes of the device (McNamara et al., 2018; McNamara et al., 2015a) and can be used to measure trunk angular motion during the delivery (Jowitt et al., 2020; McNamara et al., 2018). Variables derived from GNSS units with embedded IMUs have been shown to have a strong relationship with prescribed fast bowling intensity (McNamara et al., 2018). McNamara et al. (2018) reported a very large association between peak PlayerLoad™ measures and ball speed across a range of prescribed bowling intensities from 60% to 100% of maximum effort, as well as large to very large relationships between prescribed bowling intensity and trunk angular velocities. This research demonstrates that data derived from trunk-worn GNSS and IMUs can be adopted to provide estimations of bowling intensity, albeit focussed on upper-body movement.

Despite their utility in measuring bowling intensity (McNamara et al., 2018), trunk-worn GNSS and IMU units cannot accurately detect vertical accelerations specific to the lower limbs (Panther & Bradshaw, 2013). Assessment of lower-limb acceleration is of particular concern in high-impact activities such as fast bowling, given the inertial force experienced through the lower limbs at foot impacts (Fong & Chan, 2010). Prior fast bowling research has reported high vertical and braking forces at the back and front foot contacts of the delivery stride (Hurrion et al., 2000). Recent research has utilised tibial-mounted IMUs and reported lower time-to-peak resultant tibial acceleration at front-foot contact in fast bowlers with a history of low back pain, demonstrating a potential link between the two (Senington et al., 2020). Tibial IMUs have been shown to be valid and reliable devices in the measurement of tibial acceleration during running gait (Norris et al., 2014), and can provide insight into the assessment of running-related injuries (Murai et al., 2018) through the estimation of tibial load and bone stress (Tan et al., 2020). Although promising results using machine-learning models have been published (Hendry et al., 2020), current research suggests that ground reaction forces (GRFs) cannot be accurately estimated from trunk- or tibia-worn IMUs during cricket bowling (Callaghan et al., 2020). Despite this, accelerations measured by tibial-IMUs can still be a useful predictor of tibial loading rates and bone stress (Tenforde et al., 2020). Tibial-IMUs could therefore provide additional information to trunk-mounted microsensors in quantifying fast bowling intensity.

The aim of this study was to compare measures from a trunk-worn GNSS device and tibial-IMUs at a range of prescribed subjective bowling intensities to determine their utility in objectively measuring fast bowling intensity. It was hypothesised that greater prescribed subjective intensity would result in greater intensity measures reported from the trunk-worn GNSS and tibial-IMUs.

3.3 Methods

Subjects

An *a priori* power analysis was conducted using G*Power (Faul et al., 2007). Using the PlayerLoad^{TM} outcome variable as reported in McNamara et al. (2018) (match play: 5.70 ± 0.84 maximal effort: 6.50 ± 1.16), 15 participants were required to detect a large effect (d_z = 0.8) with 80% power (α = .05, two-tailed test) for a 'Means: Difference between two dependent means (matched pairs)' statistical test. Fifteen amateur fast bowlers (mean ± SD; age 21.0 ± 3.8 years; height 1.8 ± 0.1 m; mass 80.1 ± 8.6 kg) were therefore recruited and participated in this study. Participants were recruited from clubs within the Victorian Premier Cricket League. All participants were free from injury or other medical conditions that would have impeded participation in this study. Participants received a clear explanation of the study, and written consent was obtained. All procedures conformed to the Declaration of Helsinki and were approved by the La Trobe University's Science, Health and Engineering Low-Risk Human Ethics Subcommittee (HEC20021).

Design

This observational study required participants to complete ~24 deliveries across three subjective categories of effort: warm-up, match, and maximal intensity. Participants were permitted a self-managed warm-up (typically six deliveries) before performing three deliveries of short, good, and full-lengths at match and maximal intensities.

Procedures

Data collection was completed during routine training sessions on outdoor, natural grass/turf cricket pitches at the respective training facilities of each participating club. Deliveries were bowled towards a batter to simulate typical training and match-like scenarios. Measures of bowling intensity included ball speed, outputs from wearable microtechnology (trunk- and tibial-IMU) and a subjective measure of perceived effort (RPE). Bowling length was randomised between participants whilst intensity was always incremented from warm-up to maximal effort. Bowlers were encouraged to maintain consistent effort levels within the perceived warm-up, match, and maximal intensities. Coloured cones were used to distinguish length zones (short: >5 m from stumps; good: 3-5 m from stumps; full: <3 m from stumps). For trials to be included, the ball needed to land in the respective length zones.

Performance measures

A sports radar gun accurate to ±3% (Stalker Sport 2 Radar, Applied Concepts Inc., Richardson, TX) stationed at the batter's end of the cricket pitch was used to measure ball speed but was not communicated to the bowler during testing. After each delivery participants verbally self-reported subjective effort using the Borg 1-10 rating system (Borg, 1998), which was described to participants prior to the commencement of testing.

Participants wore a 10 Hz GNSS unit (Optimeye S5, Catapult Sports, Melbourne, Australia) fixed within a specially made elastic garment with the unit positioned on the participant's upper back. This unit facilitated the recording of PlayerLoad™, sprint speed, and run-up distance, whilst also housing a 100 Hz IMU (±16 *g* accelerometer, 2000 deg/s rate gyroscope, magnetometer) that measured angular velocity of the trunk in the roll (lateral flexion velocity [TLV]), pitch (trunk flexion velocity [TFV]) and yaw (counter-rotation, forward rotation [TRV]) axes for each delivery (McNamara et al., 2018). PlayerLoad™ was calculated by the console software as the square root of the sum of the squared instantaneous rate of change in acceleration in each of the three vectors (x, y, and z axes) divided by 100 (McNamara et al., 2018). These measures were retrieved from console software (OpenField version 1.21.1, Catapult Sports, Melbourne, Australia) post-session.

Participants wore two 1600 Hz tibial-IMUs (Blue Trident, Vicon Motion Systems, Oxford, UK). These units were attached to the distal end of the tibial plateau of each leg with double-sided adhesive tape and secured with elastic strapping. Time-stamped raw acceleration data was saved locally on each device and later downloaded using proprietary software that also captured synchronised video of each delivery (Capture.U, Vicon Motion Systems, Oxford, UK). Raw acceleration data was exported into Matlab (v. R2021a.2, MathWorks) where resultant acceleration was calculated using the three-dimensional Pythagoras' Theorem formula. Resultant acceleration was plotted in Matlab and the peak value at initial back foot contact (BF1), initial front foot contact (FF1), back foot re-contact (BF2), and front foot re-contact (FF2) for every trial was recorded and cross-checked using the time-synchronised video.

Statistical Analysis

Prior to statistical analysis, all data was converted to a percentage of the participant's peak recording for each variable. To reduce the dimensionality of the data, and identify the key variables within the dataset, a principal component analysis (PCA) was conducted. The PCA used a varimax rotation and data were tested for sample adequacy (Kaiser-Meyer-Olkin measure; >0.5) and suitability for component analysis (Bartlett test of sphericity; $\chi^2 = 917$, $p < .001$) prior to analysis (Kaiser, 1974; Ryan et al., 2020). Components were identified using an eigenvalue threshold of >1 (Ryan et al., 2020). Eight components remained above the eigenvalue threshold. Only variables with a factor loading of 0.70 were considered for inclusion while the variable chosen from each component was based on the highest factor loading and author discretion based on study aims (Ryan et al., 2020).

Mean, standard deviation, 90% confidence intervals (90%CI) and within-participant coefficient of variation (CV) were calculated for all included variables between trials of the same intensity. All statistical analyses were conducted using the Jamovi statistical platform (v1.2, The Jamovi project). A Shapiro Wilk test was used to determine whether the sample data were normally distributed. Sphericity was assessed using Mauchly's W and where violations occurred, the relevant correction was used when interpreting results ($p > .05$, no correction; $p < .05$, Greenhouse-Geisser ($\varepsilon < 0.75$) or Huynh-Feldt ($\varepsilon > 0.75$)). Two-way repeated-measures analyses of variance (ANOVA) were performed to determine whether there were any intensity-by-length interactions for any dependent variable. The magnitudes of the effect of variables in the ANOVAs were measured using partial eta-squared (η^2_p) and were described as small (.01), moderate (.06) or large (0.14) (Cohen, 1988). Where a significant interaction or main effect was detected, post-hoc pairwise comparisons with a Holm correction were performed. An alpha level of 0.05 was used for all statistical tests. The number of participants included in the analysis of each variable ranged from 12-15 based on data availability.

3.4 Results

The variables analysed in this study were extracted from the eight components presented in the PCA (Table 3.1). These variables included PlayerLoad™, four tibial-IMU variables (BF1, FF1, BF2, FF2), two torso-work IMU variables (TFV, TRV), and RPE. Additionally, the authors agreed to include ball speed in the data analysis, given its utility in differentiating between faster and slower deliveries, and because of its common reporting among other fast bowling studies (McNamara et al., 2018).

No significant interactions nor main effects of bowling length were found for any variable. There was a significant main effect of bowling intensity with large effect sizes for all variables ($p < .05$; $\eta^2_p > 0.14$; Table 3.2).

Table 3.1 Principal Component Analysis of external workload metrics in fast bowling

Component	Factor Loading
Component 1 – (Eigenvalue: 10.7)	
%Peak PlayerLoad™*	0.938
%Run-up length	0.910
%Peak FF2	0.810
%Peak TLV	0.770
Component 2 – (Eigenvalue: 5.7)	
%Peak BF1*	0.920
Component 3 – (Eigenvalue: 5.3)	
%Peak TFV*	0.912
%Peak Trunk counter-rotation velocity	0.806
Component 4 – (Eigenvalue: 4.5)	
%Peak FF1*	0.962
Component 5 – (Eigenvalue: 3.9)	
%Peak TRV*	0.918
Component 6 – (Eigenvalue: 3.0)	
% Peak FF2*	0.908
Component 7 – (Eigenvalue: 2.0)	
% Peak BF2*	0.757
Component 8 – (Eigenvalue: 1.8)	
% Peak RPE*	0.921

Abbreviations: FF2, tibial acceleration at front-foot re-contact of delivery stride; TLV, trunk lateral flexion velocity; BF1, tibial acceleration at back-foot contact of delivery stride; TFV, trunk flexion velocity; FF1, tibial acceleration at front foot contact of follow-through; TRV, trunk forward rotation velocity; BF2, tibial acceleration at back-foot re-contact of follow-through; RPE, rate of perceived exertion. * indicates variables selected for analysis.

Table 3.2 Relative microtechnology and performance outputs (mean ± SD) across bowling intensity. Results presented as percentage maximum across the cohort.

	Bowling Intensity			ANOVA			
Variable	Warm-Up	Match	Maximal	df	F	p	η2p
Peak Ball speed (%)							
Mean ± SD	86.0 ± 7.2	96.5 ± 1.2	97.0 ± 1.6	1.1, 11.8	23.9	<0.001	0.685
90% CI	82.7 - 89.3	95.9 - 97.1	96.2 - 97.8				
CV% (90% CI)	10.0 (1.7-18.3)	1.9 (1.6-2.2)	2.2 (1.4-3.1)				
Peak RPE (%)							
Mean ± SD	47.5 ± 11.2	80.3 ± 8.5	91.5 ± 7.3	2,24	142	<0.001	0.922
90% CI	42.4 - 52.6	76.7 - 83.9	88.4 - 94.6				
CV% (90% CI)	26.0 (15.7-36.2)	12.3 (10.0-14.6)	5.8 (3.3-8.3)				
Peak Trunk Metrics (%)							
PlayerLoad™							
Mean ± SD	67.8 ± 14.0	88.4 ± 7.4	90.1 ± 4.8	1.2, 16.7	49	<0.001	0.778
90% CI	61.9 – 73.7	85.2 – 91.5	88.1 – 92.1				
CV% (90% CI)	12.0 (8.0 – 16.0)	5.3 (4.1 – 6.5)	6.2 (4.9 – 7.5)				
TFV							
Mean ± SD	61.7 ± 14.2	70.2 ± 11.5	71.9 ± 9.4	2, 28	9.2	<0.001	0.396
90% CI	55.7 – 67.7	65.3 – 75.1	67.9 – 75.9				
CV% (90% CI)	16.9 (13.8-20.0)	18.3 (14.8-21.8)	18.5 (14.8-22.1)				
TRV							
Mean ± SD	68.6 ± 12.7	76.0 ± 10.4	79.5 ± 11.9	1.2, 16.5	6.2	0.019	0.308
90% CI	63.2 – 74.0	71.6 – 80.4	74.4 – 84.6				
CV% (90% CI)	14.1 (10.6-17.5)	13.8 (11.6-16.0)	12.5 (10.3-14.7)				

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Peak Tibial Acceleration (%)							
BF1							
Mean ± SD	39.2 ± 18.7	53.3 ± 17.6	57.2 ± 22.4	2, 26	11.3	<0.001	0.466
90% CI	31.0 – 47.4	45.8 – 60.8	47.7 – 66.7				
CV% (90% CI)	27.7 (21.5-34.0)	37.4 (26.4-48.3)	28.6 (19.1-38.2)				
FF1							
Mean ± SD	45.5 ± 17.1	59.0 ± 15.4	62.8 ± 14.9	2, 26	15.9	<0.001	0.551
90% CI	38.0 – 53.0	52.5 – 65.5	56.5 – 69.1				
CV% (90% CI)	20.7 (14.1-27.4)	23.0 (16.1-29.9)	24.3 (18.9-29.8)				
BF2							
Mean ± SD	46.6 ± 15.4	63.5 ± 12.2	63.8 ± 17.2	1.1, 14.7	10.1	0.005	0.438
90% CI	39.8-53.4	58.3 – 68.7	56.5 – 71.1				
CV% (90% CI)	28.6 (22.7-34.5)	26.7 (21.1-32.2)	24.1 (20.1-28.2)				
FF2							
Mean ± SD	36.3 ± 16.2	53.6 ± 12.3	59.7 ± 16.0	2, 26	21.9	<0.001	0.628
90% CI	29.2 – 43.4	48.4 – 58.8	52.9 – 66.5				
CV% (90% CI)	27.8 (21.8-33.7)	30.4 (24.4-36.5)	26.8 (21.6-31.9)				

Abbreviations: RPE, rate of perceived exertion; TFV, trunk flexion velocity; TRV, trunk forward rotation velocity; BF1, tibial acceleration at back foot contact of delivery stride; FF1, tibial acceleration at front foot contact of delivery stride; BF2, tibial acceleration at back foot re-contact of follow-through; FF2, tibial acceleration at front foot re-contact of follow-through; SD, standard deviation; CV, within-participant coefficient of variation; CI, confidence interval; df, degrees of freedom; F, F-statistic; n2p, partial eta squared.

Peak ball speed was significantly greater in the match (mean difference ± standard error; 10.5 ± 1.80%, $p < .001$) and maximal (11.1 ± 1.80%, $p < .001$) conditions compared with the warm-up condition (Figure 3.1) but were not significantly different from each other (-0.5 ± 1.80%, $p = .768$). Peak RPE was significantly different between all intensity conditions (warm-up to match: 32.8 ± 2.71%, $p < .001$; warm-up to max: 44.0 ± 2.71%, $p < .001$; and match to max: 11.2 ± 2.71%, $p < .001$).

Match and maximal intensity measures were generally greater than warm-up for each variable from the GNSS and trunk-worn IMU (Figure 3.2). PlayerLoad™ was significantly greater in the match (mean difference ± standard error; 20.6 ± 2.51%, $p < .001$) and maximal (22.3 ± 2.51%, $p < .001$) conditions compared with the warm-up condition, with no significant difference between match and maximal conditions (-1.7 ± 2.51%, $p = .499$). Peak TFV was significantly greater in the match (8.5 ± 2.56%, $p = .005$) and maximal conditions (10.2 ± 2.56%, $p = .001$) compared with the warm-up condition, but was not significantly different between the match and maximal (-1.7 ± 2.56%, $p = .518$) conditions. Peak TRV was significantly greater in the maximal condition compared with the warm-up condition (10.9 ± 3.14%, $p = .005$), but was not significantly different between warm-up and match (7.4 ± 3.14%, $p = .054$), or match and maximal conditions (-3.5 ± 3.14%, $p = .270$

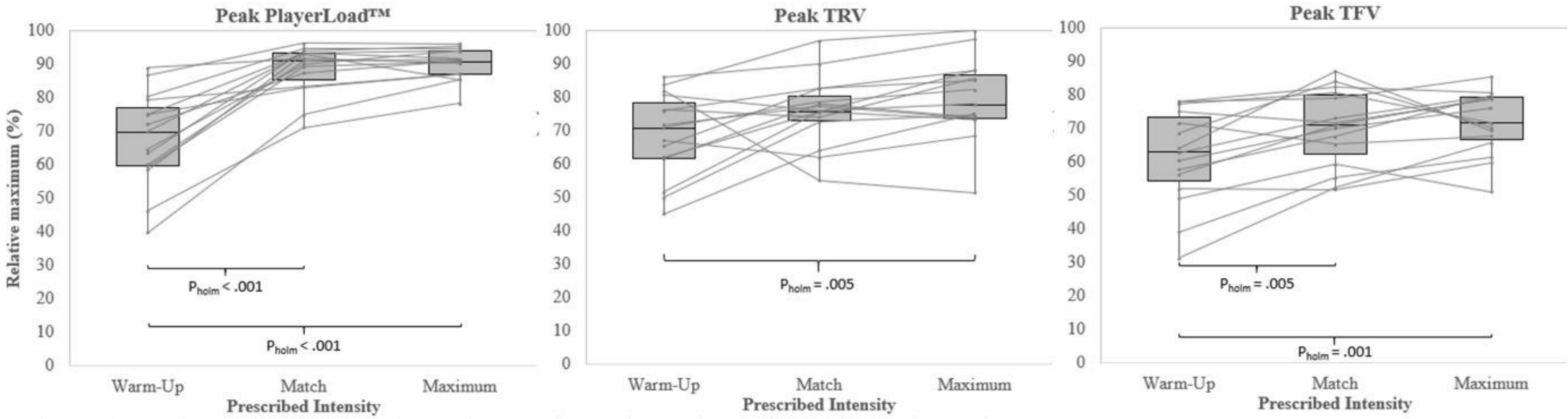

Figure 3.1 Box and whisker plots for trunk-GNSS unit measures. Boxes convey second and third quartiles representing half of the data set for each condition. Horizontal lines across boxes signify the median value for each data set. Vertical whisker lines demonstrate maximum and minimum results of each data set. Feint lines attached to each whisker represent the results of individual participants for that data set. *Sample sizes:* n = 15 for all variables. *Abbreviations:* GNSS, global navigation satellite system, TRV, trunk forward rotation velocity; TFV, trunk flexion velocity; P_{holm}, post-hoc holm test p-value.

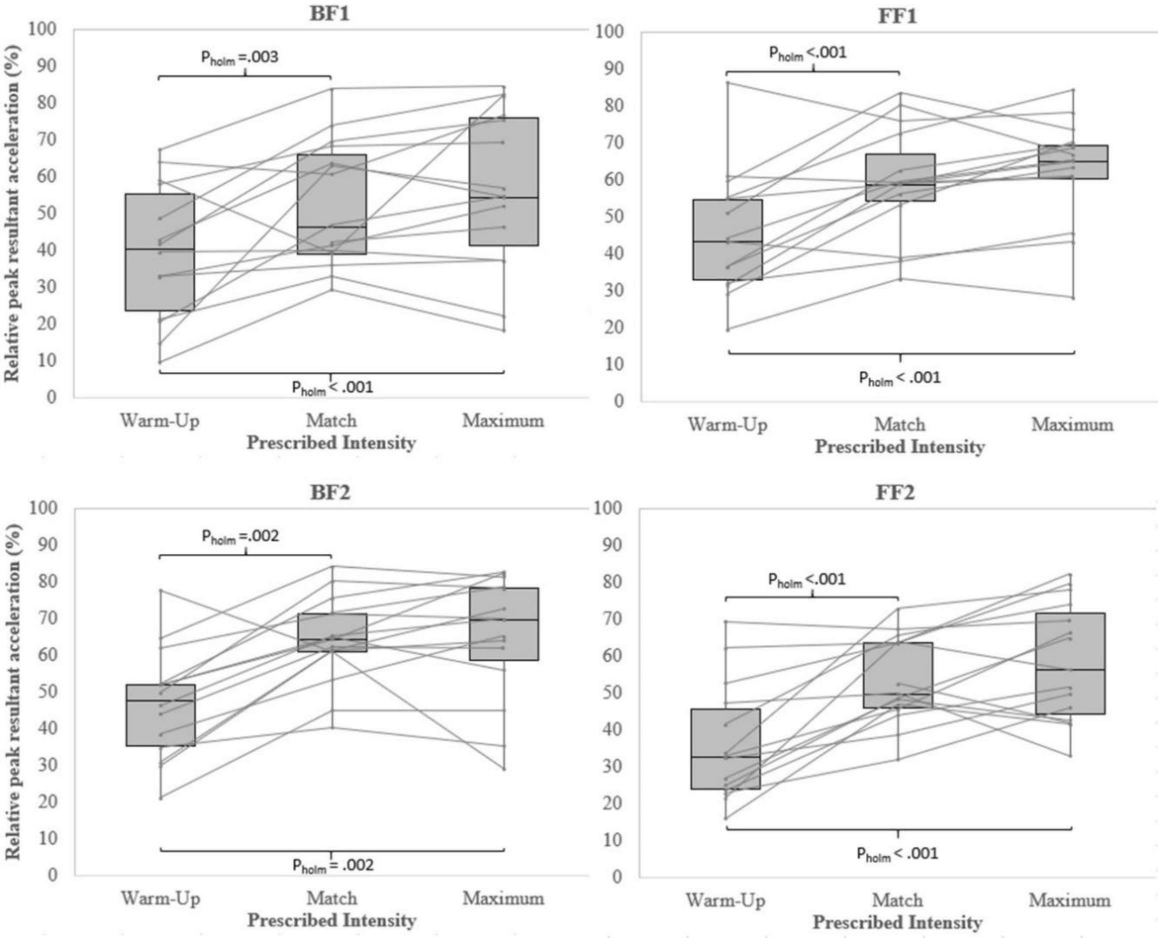

Figure 3.2 Box and whisker plots for tibial-IMU measures. Boxes convey second and third quartiles representing half of the data set for each condition. Horizontal lines across boxes signify the median value for each data set. Vertical whisker lines demonstrate maximum and minimum results of each data set. Feint lines attached to each whisker represent the results of individual participants for that data set. *Sample sizes:* n = 14 for all variables. *Abbreviations*: IMU, inertial measurement unit; BF1, tibial acceleration at back foot contact of delivery stride; FF1, tibial acceleration at front foot contact of delivery stride; BF2, tibial acceleration at back foot re-contact of follow-through; FF2, tibial acceleration at front foot re-contact of follow-through; P_{holm}, post-hoc holm test p-value.

Match and maximal intensity measures were greater than warm-up for each variable from the tibial-IMU (Figure 3.3). Tibial accelerations (FF1, BF1, FF2, BF2) were 13.5 – 17.3% ($p < .05$) higher in the match condition and 17.2 – 23.4% ($p < .05$) higher in the maximal condition compared with the warm-up condition.

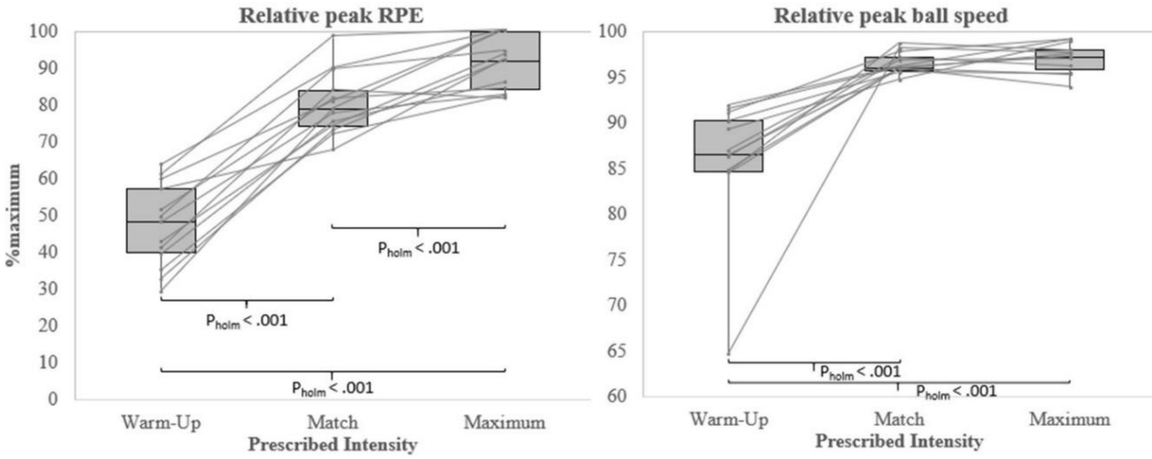

Figure 3.3 Box and whisker plots for perceived exertion and ball speed measures. Horizontal lines across boxes signify the median value for each data set. Vertical whisker lines demonstrate maximum and minimum results of each data set. Feint lines attached to each whisker represent the results of individual participants for that data set. *Sample sizes:* RPE, n = 13; ball speed, n = 12. *Abbreviations*: RPE, rate of perceived exertion; P_{holm}, post-hoc holm test p-value.

3.5 Discussion

This study sought to determine the efficacy of GNSS and trunk- and tibia-mounted IMU devices to objectively measure fast bowling intensity. Our results showed that variables derived from the trunk-IMU device (PlayerLoad™, TFV, TRV) and tibial-IMU (BF1, FF1, BF2, FF2), as well as RPE and ball speed, were significantly higher in the subjective match and maximal intensities when compared with a warm-up intensity. There were no differences between match and maximal intensities for any variable except for RPE. These findings demonstrate that variables derived from trunk- and tibial-IMU devices can be used to classify deliveries as either warm-up or match/maximal intensity.

The results of the PCA presented the majority of trunk- and tibial-IMU derived metrics in separate components. The dispersion of trunk- and tibial-IMU variables across components indicates that these outputs were uncorrelated and therefore may assess unique aspects of fast bowling intensity (Ryan et al., 2020). This highlights the importance of adopting trunk- and tibial-IMU devices to assess upper- and lower-body intensity, respectively. This notion is supported by prior research that has shown trunk-worn accelerometers are unable to accurately quantify vertical GRF (Callaghan et al., 2020). The ability to distinguish between upper and lower-body accelerations in fast bowling may allow for more accurate bowling monitoring procedures, by identifying spikes in acute bowling volume and intensity, which could lead to stress fractures and other overuse injuries (Davies et al., 2008; Hulin et al., 2014; Orchard et al., 2015). Hence, accurate reporting of acceleration requires measurement at localised sites, to identify specific body regions which may be at risk of an overuse injury.

PlayerLoad™ results in this study support the findings of prior research, where an ability to differentiate between low (warm-up) and high (match and maximal) intensity bowling efforts – as well as a large effect size – were demonstrated using the metric (McNamara et al., 2018; McNamara et al., 2015a). However, PlayerLoad™ was unable to differentiate match and maximal intensities, perhaps correctly conveying the lack of difference between the two intensities. This finding supports previous research that has demonstrated that fast deliveries bowled at 70% of perceived-maximal intensity can produce a near-maximal ball speed, despite the perception of less effort (Feros et al., 2021). The similar changes from warm-up to match and maximal intensities for PlayerLoad™, RPE, and ball speed demonstrate a similarity between the prescribed, perceived and performed intensity in this study, which has also been shown previously (McNamara et al., 2018). Additionally, the CVs for PlayerLoad™, RPE, and ball speed were found to be greatest during the warm-up condition, which is likely due to greater tendencies of bowling variability at lower intensities, before converging towards a ‘ceiling’ at higher intensities (Jowitt et al., 2020; McNamara et al., 2018). CV results in ball speed across intensities remained relatively low, in comparison to variability measures reported for the peak trunk angular velocities and peak resultant tibial accelerations. McNamara et al. (2018) suggests the relatively low variability in ball speed, in comparison to microtechnology outputs across higher intensities, could be attributed to the fast bowlers’ ability to maintain consistent delivery velocities despite subtle changes in technique. Ultimately, PlayerLoad™ remains a unique and useful measure for whole-body classifications of intensity in fast bowling; however, researchers should also consider specific upper and lower body segment variables, to assess and quantify bowling intensity more accurately.

The findings from this study showed significant changes in tibial acceleration between warm-up to match and maximal intensities, indicating the ability to quantify intensity between these conditions. Prior assessments of tibial acceleration during running gait have shown that as running speed increases, so does the resultant GRF, leading to greater tibial loads and bone stress experienced in the lower limbs (Van den Berghe et al., 2019). Whilst tibial-IMUs cannot accurately estimate GRF, increases in tibial acceleration have shown to be a good estimate of tibial load and increased bone stress (Tenforde et al., 2020). Previous research has sought to investigate a potential relationship between tibial load and low-back injury risk in cricket fast bowling, however, the true effect of lower-limb load on the low back remains unclear (Senington et al., 2020). The ability to quantify lower-limb acceleration using tibial-IMU in the current study provides evidence of a relationship between increased intensity and increased tibial acceleration, outlining potential increases in tibial load during higher-intensity deliveries. This may be demonstrative of an increased injury risk during fast deliveries of greater intensity. Furthermore, the PCA results demonstrated that the tibial acceleration at the foot contacts (BF1, FF1, BF2, FF2) were uncorrelated, highlighting the importance of assessing both delivery stride and follow-through contacts when considering tibial load of a fast delivery. This study was the first to report tibial accelerations at back and front foot re-contacts after the delivery stride. Research is required to assess the differences in tibial accelerations and GRFs experienced during these foot contacts, as this may provide additional information on the link between ground contact forces and injury risk in cricket fast bowlers.

Trunk angular velocity is a particularly important consideration for fast bowling researchers, given the prominence of lumbar spine injuries reported amongst the fast bowling population (Alway et al., 2021; Davies et al., 2008; Orchard et al., 2015). In our study, TFV significantly increased from warm-up to match and maximal conditions, whilst TRV only significantly increased between warm-up and maximal intensity. These findings indicate increased trunk motion (particularly trunk flexion) are associated with increases in bowling intensity. This supports existing research which has demonstrated a relationship between trunk angular velocities – specifically upper-trunk flexion (Worthington et al., 2013b), – in fast bowling delivery intensity and ball speed (McNamara et al., 2018). A possible explanation of our result is that a desire to bowl faster at the higher bowling intensities led to faster trunk angular velocity measures, and therefore higher activation of the trunk muscles. Differences in trunk angular velocities can also depend on the side-on/front-on/mixed technique of the bowler (Portus et al., 2004), however, this was not assessed in the current study. Although trunk angular velocity has been shown to be related to subjective delivery intensity, its utility as an objective measure of bowling intensity is spurious using IMU-derived data only and may be confounded by the technique used by a particular bowler.

Limitations

A consideration of the study is the potential ambiguity of perceived intensity levels between participants. Whilst the external load measures in this study are reported as individual percentage-maximum, the perception of the warm-up and match intensities may have varied between participants. This may have been particularly apparent during the match intensity condition, as during competition, bowling effort could vary depending on strategy, match situation or fatigue level. Another consideration of this study is that there were minor variations in the data collection procedures between sessions. To accommodate the training needs of the volunteering clubs, batters were rotated through data collection at the discretion of the club coaches. This sometimes resulted in the involvement of multiple batters in one session – some with alternating stance, preferred batting side, and stature. However, the mixed allocation of batters to the batting crease may also be somewhat replicable of match-play and training, where bowlers will deliver to new batters after a dismissal or change of ends or as they rotate through training nets.

3.6 Practical Applications

PlayerLoad™ and tibial acceleration measures presented in this study can be used to categorise bowling delivery intensity and provide greater context for bowling delivery intensity classification by coaches and athletes. The results of the PCA show that PlayerLoad™ and tibial acceleration represent unique aspects of the fast bowling delivery intensity and could therefore be useful in player monitoring or return from injury assessments specifically relating to the upper- and lower-body, respectively. Utilisation of these variables could be applied towards more evidence-based training prescription and monitoring, with consideration towards recent training performance.

3.7 Conclusion

This study found that trunk-mounted and tibia-mounted IMU devices can accurately discriminate between low- and high-intensity bowling deliveries, using peak upper- and lower-body intensity measures including PlayerLoad™, trunk angular velocities, and tibial accelerations. Changes in delivery length did not affect fast bowling intensity. Further research should seek to explore the validity of these measures amongst the elite fast-bowling population, in both male and female cricketers.

Chapter Four

Comparing tibial accelerations between delivery and follow-through foot strikes in cricket fast bowling

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4.1 Abstract

The foot strikes of the fast bowling delivery stride produce large ground reaction forces and may be linked to injury, yet the biomechanics of the follow-through are unknown. This study assessed tibial accelerations across delivery and follow-through foot strikes in fast bowlers and evaluated relationships between these measures and several established fast bowling intensity metrics. Fifteen sub-elite male fast bowlers performed deliveries at prescribed warm-up, match, and maximal intensities. Tibial accelerations were measured using tibial-mounted inertial measurement units and recorded at back foot contact, front foot contact, back foot re-contact, and front foot re-contact. A trunk-worn global navigation satellite system unit measured PlayerLoad™, run-up speed, and run-up distance. Ball speed and rate of perceived exertion measures were also recorded for each delivery. A linear mixed model showed statistical significance between prescribed intensities ($p < .001$) and foot strikes ($p < .001$). Tibial accelerations showed significant, positive increases with changes in prescribed intensity ($p < .05$). The greatest magnitude of tibial acceleration was found at back foot re-contact. Weak correlations were found between foot contacts (r = 0.2-0.4). The greatest magnitude of tibial acceleration reported at BF2 may have implications for injury incidence and, therefore, represents an important avenue for future fast bowling research.

4.2 Introduction

Fast bowlers have the highest injury incidence of all cricketers, particularly in the low back and lower limbs (Davies et al., 2008; Orchard et al., 2015). Whilst some fast bowling injuries can be attributed to poor technique (Alway et al., 2021; Portus et al., 2004), excessive bowling volumes at repeated high-intensity efforts are also linked to injury incidence (Hulin et al., 2014; Orchard et al., 2015). The fast bowling action is particularly precarious at the initial front foot strike of the delivery stride (FF1), where bowlers can experience vertical ground reaction forces (GRFs) of up to eight times their body weight (Portus et al., 2004). These forces can be experienced more than 300 times per multi-day match, increasing the injury risk (Orchard et al., 2009).

The hypothesised link between large peak GRFs at FF1 and injury (Bartlett et al., 1996) has led to a research focus on delivery stride biomechanics in fast bowling (Hurrion et al., 2000; Worthington et al., 2013a). Whilst research has demonstrated that large GRFs occur at both initial back foot strike of the delivery stride (BF1) and FF1 (Hurrion et al., 2000; Worthington et al., 2013a), current fast bowling research has afforded little consideration to the follow-through foot strikes occurring after ball release. Studies in golf and baseball pitching have shown that decelerations occurring in the follow-through phases of those techniques are likely responsible for high muscle and joint loading, contributing to injury incidence in athletes of those sports (Pappas et al., 1985; Steele et al., 2018). Given the fast rate of linear acceleration during the run-up phase of pace bowling (Bartlett et al., 1996; Worthington et al., 2013a), and the requirement for bowlers to decelerate their centre of mass and regain balance after ball release, it is possible that the follow-through impacts could be as large as those seen in the delivery stride. If this is true, these impacts could be contributing to the high prevalence of stress-related injuries currently observed among the fast bowling population.

Prior fast bowling research has utilised force platforms to analyse GRFs of the delivery stride (Hurrion et al., 2000; King et al., 2016; Worthington et al., 2013a). Whilst the ability to accurately measure these forces allows for a detailed analysis of joint loading, the force platform is not practical or flexible, predominantly being restricted to use in the laboratory. Inertial measurement units (IMUs) are small, wearable devices that house a triaxial accelerometer, gyroscope, and magnetometer, that have been utilised in the assessment of other high-impact activities such as running, ballet, and gymnastics (Campbell et al., 2020; Hendry et al., 2020; Tenforde et al., 2020). These devices offer the opportunity to assess body segment accelerations in field-based settings. Current research surrounding the utility of wearable-IMU accelerations to estimate GRF is inconsistent (Callaghan et al., 2020; Hendry et al., 2020). Recent research that assessed drop landings in ballet dancers showed good agreement (root-mean-square error of 0.29 body weights) between a force platform and estimated forces derived from a sacrum-mounted IMU (Hendry et al., 2020). However, in fast bowling research, estimates of GRF are unable to be accurately attained from trunk- or tibia-IMUs (Callaghan et al., 2020). Despite this, there is an acceptable level of error and a positive correlation between tibial-IMU force signatures and discrete GRF measures (Callaghan et al., 2020). Research in running (Tenforde et al., 2020) and gymnastics (Campbell et al., 2020) has demonstrated the utility of tibial-IMU acceleration to provide a surrogate for loading rate, to infer GRF and tibial load. Whilst a method to accurately measure GRF using wearable IMUs is yet to be established in fast bowling, based on Newton's second law of motion (*force = mass × acceleration)*, significant changes in tibial acceleration should at least be indicative of changes in tibial load.

The application of IMUs to measure tibial accelerations through the delivery stride and follow-through across different bowling intensities has previously been shown (Epifano et al., 2021). Using a principal component analysis, tibial acceleration at each foot strike across the delivery stride and follow-through appear to represent a unique aspect of fast bowling performance, and are shown to differentiate across delivery intensities (Epifano et al., 2021). Based on these findings, further research into the magnitude of peak tibial acceleration across the delivery stride and follow-through is warranted.

Additionally, recent fast bowling intensity research has sought to establish metrics that can objectively determine the physical demand of pace deliveries (Epifano et al., 2021; McNamara et al., 2018). In a within-participant analysis of 15 semi-professional fast bowlers, a principal component analysis showed that relative-maximum data of ball speed, PlayerLoad™, RPE and tibial acceleration at BF1, FF1, back foot re-contact in the follow-through stride (BF2) and front foot re-contact in the follow-through stride (FF2), can each represent unique aspects of the physical load in pace deliveries (Epifano et al., 2021). Whilst some fast bowling research has demonstrated associations between run-up speed/trunk linear acceleration, GRF magnitude at BF1 and ball release speed (Ferdinands et al., 2010; Glazier & Worthington, 2014; Middleton et al., 2016; Salter et al., 2007; Worthington et al., 2013b), the relationships between trunk-metrics, ball speed, prescribed bowling intensity and tibial kinematic data is yet to be investigated. An understanding of the potential interplay between tibial kinematic data and upper-body/external fast bowling metrics may improve the accuracy of intensity quantification for pace deliveries performed in field settings.

This study aimed to compare the peak resultant tibial accelerations at BF1, FF1, BF2, and FF2. A secondary aim was to investigate the relationships between these variables and the prescribed bowling intensity, as well as other commonly reported measures of bowling intensity. It was hypothesised that there would be an effect of foot strike and prescribed intensity on peak resultant tibial acceleration, and that there would be significant relationships between peak resultant tibial acceleration and other commonly reported measures of bowling intensity.

4.3 Methods

This observational study is a secondary analysis of Epifano et al. (2021) (Chapter 3). The bowling protocol was identical to Epifano et al. (2021) and because that study showed delivery length to be a non-factor, bowling data were collapsed in the statistical model for this study.

Participants

Fifteen amateur male fast bowlers (mean ± SD; age 21.0 ± 3.8 years; height 1.8 ± 0.1 m; mass 80.1 ± 8.6 kg) participated in this study. Participants were recruited from clubs within the Victorian Premier Cricket League. All participants were free from injury or other medical conditions that would have impeded participation in this study. Participants received a clear explanation of the study, and written consent was obtained. All procedures conformed to the Declaration of Helsinki and were approved by the La Trobe University's Science, Health and Engineering Low-Risk Human Ethics Subcommittee (HEC20021). An a priori sensitivity analysis was conducted using G*Power (Faul et al., 2007). With 15 participants and 80% desired power, effect-size sensitivity analysis returns that this power will be achieved for effects $f \geq 0.32$ ($\eta^2_p = 0.1$).

Design

This observational study required participants to complete ~24 deliveries across three subjective categories of effort: warm-up, match, and maximal intensity. For each category of effort, participants were instructed to bowl at an intensity level that represented their typical performance at that perceived effort-level i.e., typical warm-up and match-play deliveries, and maximal effort deliveries. Participants were permitted a self-managed warm-up (typically six deliveries) before performing nine deliveries at match and maximal intensities. A self-managed warm-up was permitted to allow the participants to 'build' into match-intensity efforts, but was restricted to a maximum of six deliveries. Each participant performed a minimum of 22 trials, as some elected to bowl fewer warm-up deliveries having already completed warm-up exercises as part of their club training session, separate to the study protocol. Some participants performed more deliveries based on unsuccessful trials, but only successful trials were used for analysis (n = 400).

Procedures

Data collection was completed during routine training sessions on outdoor, natural grass/turf cricket pitches at the respective training facilities of each participating club. Deliveries were bowled towards a batter to simulate typical training and match-like scenarios. Measures of bowling intensity included ball speed, a subjective measure of perceived exertion (RPE), and outputs from wearable microtechnology (tibial- and trunk-IMU). Participants were encouraged to gradually increase effort level in the warm-up condition, but maintain consistent effort within the perceived match, and maximal intensities.

Performance measures

A sports radar gun accurate to ±3% (Stalker Sport 2 Radar, Applied Concepts Inc., Richardson, TX) stationed at the batter's end of the cricket pitch was used to measure ball speed, but was not communicated to the bowler during testing. After each delivery participants verbally self-reported subjective RPE using the Borg 1-10 rating system (Borg, 1998) which was described to participants prior to the commencement of testing.

Participants wore two 1600 Hz tibial-IMUs (Blue Trident, Vicon Motion Systems, Oxford, UK). These units were attached to the distal end of the tibial plateau of each leg (Tenforde et al., 2020) with double-sided adhesive tape and secured with elastic strapping. Time-stamped raw acceleration data were saved locally on each device and later downloaded using proprietary software that also captured synchronised video of each delivery (Capture.U, Vicon Motion Systems, Oxford, UK). Raw acceleration data was exported into Matlab (v. R2021a.2, MathWorks) where resultant acceleration was calculated using the three-dimensional Pythagoras' Theorem formula. Resultant accelerations were plotted in Matlab and the peak values at BF1, FF1, BF2, and FF2 for every trial were recorded and cross-checked using the time-synchronised video.

Participants also wore a 10 Hz GPS unit (Optimeye S5, Catapult Sports, Melbourne, Australia) fixed within a specially made elastic garment with the unit positioned on the participant's upper back. This unit facilitated the recording of sprint speed and run-up distance, whilst also housing a 100 Hz (±16 *g*) accelerometer to measure PlayerLoad™. PlayerLoad™ was calculated by the console software as the square root of the sum of the squared instantaneous rate of change in acceleration in each of the three vectors (x, y, and z axes) divided by 100 (McNamara, Gabbett, Blanch & Kelly, 2018; Chapter Three). These measures were retrieved from console software (OpenField version 1.21.1, Catapult Sports, Melbourne, Australia) post-session.

All measurement devices were utilised using their original factory calibration.

Statistical Analysis

Statistical analyses were conducted using the Jamovi statistical package (Jamovi version 2.0.0.0, Jamovi Project, 2021). Linear mixed models (LMM) were used to examine whether peak resultant tibial accelerations differed between foot-strike types across the three bowling intensities. The model residuals were checked against a normal distribution by visual inspection of a Quantile-Quantile plot. The outcome variable did not approximate a normal distribution and was therefore log-transformed. The LMM included fixed effects of foot strike and intensity, and a random intercept for participant (R version 4.0.1, 2020). The differences between foot strike type and intensity were assessed with Holm-corrected post-hoc tests. In addition, repeated measures correlations (using the *rmcorr* package, 0.4.4) were conducted to examine the common within-subject association across measures. Correlation effect sizes were described using the Cohen (1988) convention: small (r = 0.1-

0.29), moderate (r = 0.3-0.49) or large (r > 0.5). The number of participants included in the analysis of each variable ranged from 12-15 based on data availability.

4.4 Results

The results of the LMM found no significant effects for the interaction between foot strike and intensity. The model was therefore refitted to examine the main effects of foot strike type and intensity on peak resultant tibial acceleration. Model fixed-effects parameters and random effects variance components were back-transformed.

Significant main effects for foot strike ($F(3, 1580) = 97.1$, $p < .001$) and intensity ($F(2, 1581) = 92.7$, $p < .001$) were identified in the refitted model. The largest magnitude of tibial acceleration was observed at BF2, followed by FF1, FF2, and BF1 (Figure 4.1), with only FF1 and FF2 not being significantly different to each other ($p = .417$). Peak resultant tibial accelerations in the maximal condition (925 ± 508 m/s^2) were significantly greater than that in the match (882 ± 511 m/s^2, $t = -2.10$, $p = .036$) and warm-up (605 ± 407 m/s^2, $t = 13.11$, $p < .001$) conditions, with the match condition also being greater than the warm-up condition ($t = 11.56$, $p < .001$).

All measured variables increased in magnitude with intensity (Table 4.1 and Table 4.2).

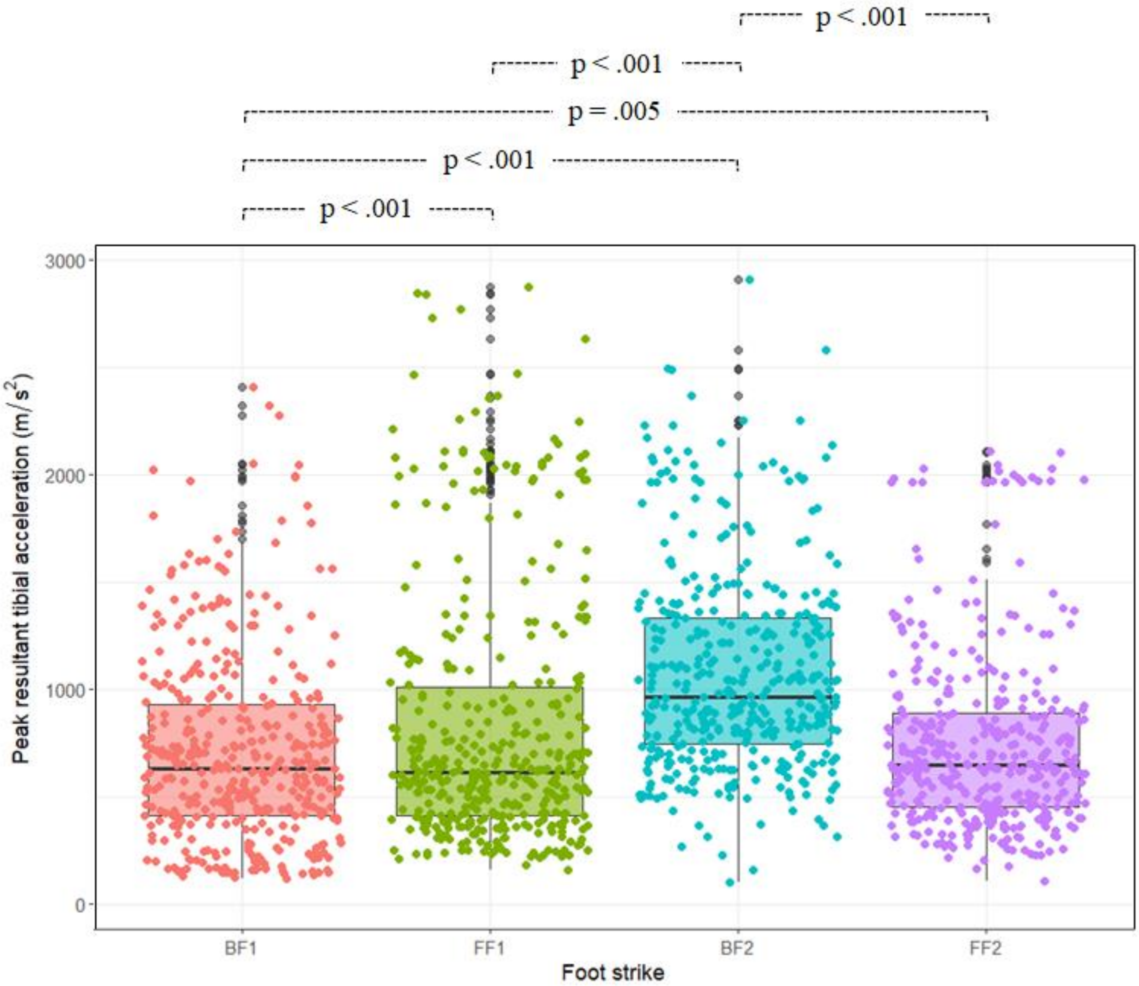

Figure 4.1 Box and whisker plot representing magnitudes of peak resultant tibial acceleration between foot strikes across all intensities. Boxes convey second and third quartiles representing half of the data set for each condition. Vertical whisker lines demonstrate the first and fourth quartiles of data. Horizontal black lines within boxes signify the median value for each data set. Scatter plots represent peak resultant tibial accelerations from every trial and are categorised based on foot strike type. *Sample sizes:* n = 400 for all foot strikes. *Abbreviations:* BF1, tibial acceleration at back foot contact of delivery stride; FF1, tibial acceleration at front foot contact of delivery stride; BF2, tibial acceleration at back foot re-contact of follow-through.

Table 4.1 Peak resultant tibial acceleration across cricket fast bowling intensities at each foot strike. Data are Mean ± standard deviation (SD) and 95% confidence intervals [95%CI]; n = 14.

	Bowling Intensity		
Peak Tibial Acceleration (m/s^2)	Warm-Up	Match	Maximal
BF1			
Mean ± SD	529 ± 282	741 ± 362*	791 ± 416*
[95% CI]	[382-677]	[558-924]	[580-1001]
FF1			
Mean ± SD	691 ± 570	879 ± 606*	920 ± 577*
[95% CI]	[392-989]	[572-1185]	[628-1212]
BF2			
Mean ± SD	810 ± 348	1139 ± 319*	1143 ± 406*
[95% CI]	[628-992]	[977-1300]	[937-1349]
FF2			
Mean ± SD	476 ± 183	781 ± 320*	829 ± 293*
[95% CI]	[381-572]	[619-943]	[681-977]

* indicates significant difference ($p < .05$) from warm-up intensity. No significant differences were found between match and maximal intensities. *Abbreviations:* BF1, back foot contact of delivery stride; FF1, tibial acceleration at front foot contact of delivery stride; BF2, tibial acceleration at back foot re-contact of follow-through.

Table 4.2 Fast bowling outputs across intensities. Data are Mean ± standard deviation (SD) and 95% confidence intervals [95%CI]; n = 15 (ball speed n = 12).

	Bowling Intensity		
Variable	Warm-Up	Match	Maximal
Ball Speed (km/h)			
Mean ± SD	104 ± 6.1	114 ± 6.7*	114 ± 6.8*
[95% CI]	[101-107]	[110-117]	[110-118]
RPE			
Mean ± SD	4.7 ± 1.1	7.8 ± 0.9*	8.9 ± 0.9*^
[95% CI]	[4.1-5.3]	[7.3-8.2]	[8.4-9.3]
PlayerLoad™ (au)			
Mean ± SD	2.9 ± 0.5	3.8 ± 0.5*	3.9 ± 0.5*
[95% CI]	[2.7-3.2]	[3.6-4.1]	[3.7-4.2]
Run-up speed (m/s)			
Mean ± SD	5.1 ± 0.5	6.2 ± 0.4*	6.3 ± 0.4*^
[95% CI]	[4.8-5.4]	[6.0-6.4]	[6.1-6.5]
Run-up distance (m)			
Mean ± SD	24.4 ± 5.0	32.2 ± 2.8*	32.9 ± 3.5*
[95% CI]	[21.9-26.9]	[30.8-33.6]	[31.1-34.7]

* indicates significant differences ($p < .05$) from warm-up intensity. ^ indicates significant difference ($p < .05$) from match intensity. *Abbreviations:* RPE, rate of perceived exertion.

The results of the repeated-measures correlations identified significant associations among all variables, ($p < .02$; Figure 4.2). Correlations between variables appear in clusters of large, moderate, and small effect sizes, with the strongest correlations between ball speed, PlayerLoad™, RPE, run-up distance, and run-up speed (r = 0.62 – 0.93). Moderate correlations (0.30 – 0.43) were observed between foot strike tibial accelerations and the other tested variables, whilst correlations within the foot strike accelerations were small (0.12 – 0.23).

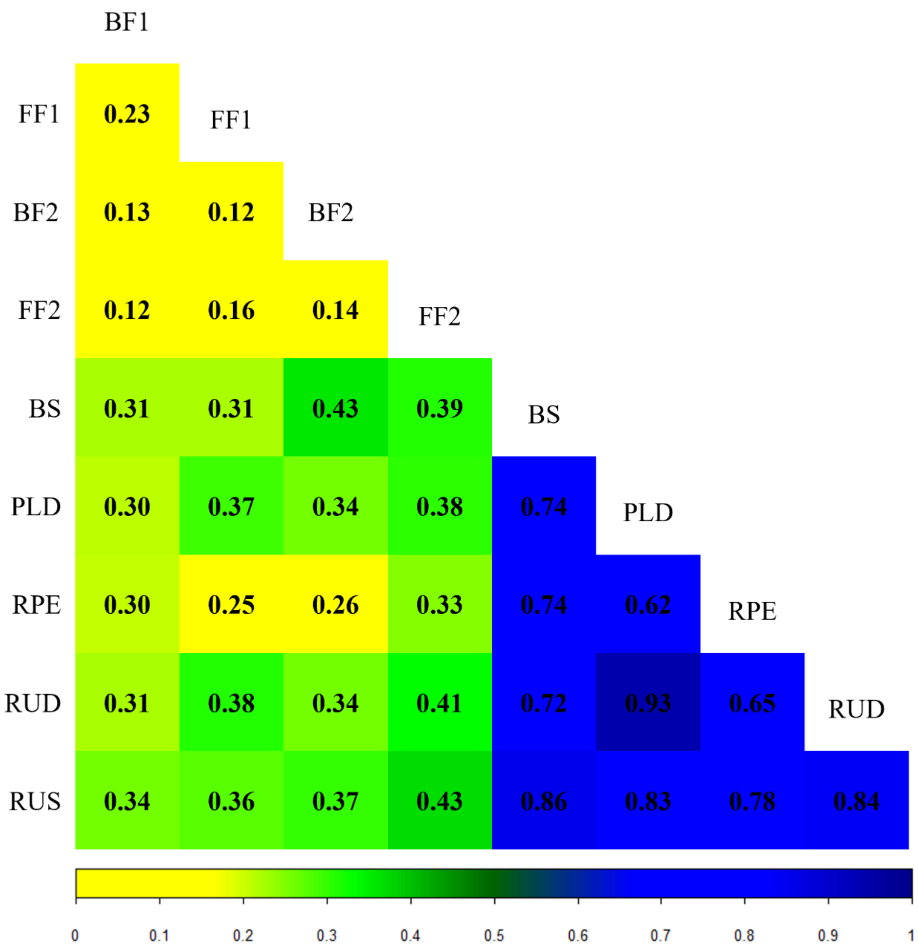

Figure 4.2 Repeated-measures correlations of assessed fast bowling variables. Positive, significant correlations were observed between all variables ($p < .02$). The coloured scale represents the strength of correlation (from yellow (small) to blue (large)). *Abbreviations*: BF1, tibial acceleration at back foot contact; FF1, tibial acceleration and front foot contact; BF2, tibial acceleration at back foot re-contact; FF2, tibial acceleration at front foot re-contact; BS, ball speed; PLD, PlayerLoad™; RPE, rate of perceived exertion; RUD, run-up distance; RUS, run-up speed.

4.5 Discussion and Implications

This study investigated differences in peak resultant tibial accelerations across the foot strikes of the fast bowling delivery stride and follow-through. The greatest magnitude of peak resultant tibial acceleration was reported at BF2, followed by FFI, FF2, and BF1. All measures were shown to increase with prescribed intensity (Tables 4.1 & 4.2) and were positively correlated with each other ($r = 0.12$-0.93), supporting our hypotheses.

Prior fast bowling research has focused mainly on the impacts of the delivery stride foot strikes (Alway et al., 2021; Callaghan et al., 2021; Callaghan et al., 2020; Portus et al., 2004; Worthington et al., 2013a), with little consideration afforded to the follow-through. Epifano et al. (2021) was the first study to assess both the delivery and follow-through foot strikes, and reported that foot strikes of the follow-through may represent a unique aspect of the fast bowling delivery. In the current study, the greatest magnitude of resultant tibial acceleration across both the delivery and follow-through foot strikes was found to occur at BF2. This may be due to the kinematics of the trunk and lower limbs following FF1. Fast bowlers typically deliver a ball with a rapidly flexing trunk from the beginning of the delivery stride through to ball release (Ranson et al., 2008). This is a function of linear-to-angular momentum transfer from the lower-limb segments involved in the run-up, to the trunk and upper-limb segments (Ferdinands et al., 2010; Zhang et al., 2011). At BF1 of the delivery stride, the fast bowler's rear leg is passive, whereby the knee flexes to dissipate GRF, rather than actively extending to generate a 'thrust' and maintain linear momentum (Ferdinands et al., 2014). Ferdinands et al. (2014) suggests that after the moment of FF1, when the back foot leaves the ground, flexion of the back knee and hip continue the linear momentum of the body's COM. After ball release, the bowler's linear momentum would continue forward and downward due to the flexing trunk, whilst the back leg trails behind the COM. To regain balance and produce a stable deceleration in the follow-through, the trailing leg would need to rapidly accelerate ahead of the COM and strike the ground, likely leading to the higher tibial acceleration at BF2. Given the proportionate relationship between force, mass, and acceleration (Newton's Second Law), it is likely that the greater magnitude of tibial acceleration at the BF2 strike is representative of a larger force load which may also contribute to injury development. Furthermore, Figure 4.1 shows that FF2 is not significantly different to FF1, indicating a similar magnitude of tibial acceleration reported at either foot strike. Assuming a positive relationship between peak tibial acceleration and GRF, the results may be representative of similar tibial loads at FF1 and FF2. If true, this would indicate that in overlooking FF2, prior research has potentially missed half of the total front-leg load through the delivery and follow-through strides. Hence, assessment of tibial loads at both the delivery and follow-through foot strikes is necessary, to report fast bowling tibial loads more accurately.

Existing research has typically focused on biomechanical factors from the beginning of the run-up to ball release, specifically at FF1 where vertical GRF can be as great as eight body weights (Alway et al., 2021; Callaghan et al., 2021; Callaghan et al., 2020; Portus et al., 2004; Worthington et al., 2013b) and rapid trunk lateral flexion is observed (Bayne et al., 2016; Ranson et al., 2008). Injury development in fast bowling is multi-factorial (Elliott et al., 1992), although the concurrence of rapid trunk lateral flexion and large GRFs at FF1 has long been presumed as a key contributing factor to low back injury (Bartlett et al., 1996). Previous research has associated technique factors, such as hip and shoulder alignment through the delivery stride, to bony and intervertebral disk abnormalities in the lumbar spine (Elliott et al., 1992). The peak magnitude of resultant tibial acceleration observed at BF2 in this study may be indicative of a greater tibial load at this foot strike compared with FF1. Future research is required to determine whether the GRFs at BF2 are of similar magnitude to FF1. If large GRF measurements are observed in the follow-through, this could have significant implications for future fast bowling intensity/injury research, as the follow-through may contribute a substantial portion of the total lower-limb load in individual deliveries and potentially contribute to low back injury.

The small correlations observed between the within-participant tibial-acceleration measures ($r = 0.12$-0.23) in the present study demonstrate a weak association among foot strikes. This finding reflects the outcomes of the principal component analysis presented in (Epifano et al., 2021), where foot strikes (BF1, FF1, BF2, FF2) were presented in separate components, thus representing unique aspects of bowling performance. This suggests that it may be appropriate to examine these elements of the bowling delivery separately, as they may represent different constructs. Prior research has attributed differences in GRF between delivery-stride foot strikes to changes in lower-limb geometrics and kinematics, relative to the bowler's COM (Ferdinands et al., 2010). Additional research has reported 'plant angle' (the angle between the projection of the hip to the ankle joint against the global vertical) is responsible for 63% of between-participant variation in peak vertical GRF at

FF1 (Worthington et al., 2013a). Whilst the current study did not measure COM velocities, joint angles, or force, characteristic changes in these technique factors across the delivery and follow-through foot strikes are likely responsible for the differences reported in resultant tibial acceleration. Small correlations reported among the foot strikes in this study demonstrate the importance of both delivery and follow-through stride assessment, as each foot strike may uniquely contribute to the physical demand of the fast delivery.

A negative change in COM acceleration across the fast bowling delivery stride is a key parameter of ball speed development (Glazier & Worthington, 2014; Worthington et al., 2013b), allowing for sequential transfer of kinetic energy from the lower- to upper-body segments (Ferdinands et al., 2010). In the current study, correlations between tibial accelerations, run-up speed, and ball speed were relatively similar ($r = 0.31$-0.43, moderate), while large correlations between PlayerLoad™, run-up distance, and run-up speed ($r = 0.72$-0.86) were expected based on how PlayerLoad™ is calculated. These correlation results align with previous research findings, which demonstrated a positive association between run-up speed, peak vertical and braking GRFs at FF1, and ball speed (Glazier & Worthington, 2014; Middleton et al., 2016; Salter et al., 2007; Worthington et al., 2013a). A positive relationship between run-up speed and ball speed demonstrates that bowlers who run up faster are able to produce a greater amount of linear momentum that could be converted into ball speed (Glazier & Worthington, 2014; Salter et al., 2007; Worthington et al., 2013b), via the segment sequencing method (Ferdinands et al., 2010; Zhang et al., 2011). Using three-dimensional motion-analysis technology and tibial acceleration measurement, a further investigation of run-up speed, trunk angular velocity, ball release speed, and foot strike acceleration across intensities could provide a better understanding of the potential interplay between these variables and may provide an insight into optimum fast bowling technique and mechanical load across varying delivery efforts.

Finally, research has found a concordance between prescribed and perceived fast bowling effort, whereby bowlers perceive delivery effort to be easier than the actual measured effort when a longer training program is planned (Feros et al., 2021). The current study reported an overall large correlation between RPE and ball speed, however, whilst RPE significantly increased from match to maximal intensity, ball speed remained stable. These findings demonstrate that while greater prescribed intensities also typically require greater perceived and physical effort, a maximal bowling effort is potentially not necessary to produce near maximal ball speed. With this knowledge, coaches could improve training by programming sessions to manage the psychophysiological levels of the athlete and avoid potential consequences of overtraining. This approach could maximise training adaptations by reducing the perceived effort of the fast bowler without a cost to the actual bowling intensity. This, in turn, could result in more quality fast bowling repetitions whilst maintaining training volume, to better condition the athlete and potentially reduce the risk of injury.

Limitations

A potential limitation of this study is the subjectivity of perceived warm-up and match intensity effort between participants. In the warm-up condition, participants were permitted to bowl at an effort level of their discretion, before entering the match condition where a consistent effort level was encouraged. It is possible that the interpretation of 'warm-up' and 'match' intensity efforts may have differed between participants, leading to differences in actual performed intensity. Additionally, it is also acknowledged that the instruction of a self-regulated warm-up (maximum 6-deliveries) may have led to differences in total warm-up deliveries bowled between-participants. The authors believe that in allowing the participants to regulate the warm-up deliveries to their own discretion, the results should better-reflect 'warm-up intensity' efforts typical of a training session in practice nets, of which our method of delivery intensity quantification is designed for. Furthermore, varied trial totals between-participants should not have affected the within-participant, linear mixed model data analysis conducted in this study.

4.6 Conclusion

This study compared peak resultant tibial accelerations across the delivery and follow through foot strikes of the fast bowling action and assessed within-participant correlations between tibial measures and other common bowling intensity metrics. The greatest magnitude of resultant tibial acceleration occurred at BF2, while tibial acceleration at FF2 was not significantly different to FF1. These are novel findings in fast bowling research, as tibial kinematics in the follow-through have not previously been assessed. Further research should determine the reliability of intensity quantification via tibial acceleration data between sessions and investigate whether large magnitudes of tibial acceleration at BF2 and FF2 in this study, are also representative of large tibial loads.

Chapter Five

Conclusion

5.1 Thesis summary and contributions

This thesis investigated a novel method of intensity quantification for fast bowling deliveries, involving lower-limb assessment via tibial-mounted inertial measurement units (IMUs). Previous research demonstrates the utility of trunk-mounted global navigation satellite system (GNSS) units to classify prescribed bowling intensity (McNamara et al., 2018), however, trunk units do not enable accurate kinematic assessment of the lower limbs. Whilst some existing research has assessed lower-limb impacts in fast bowling (Callaghan et al., 2020; Worthington et al., 2013a), use of force platform technology limits this practice to the laboratory setting. Whilst not an accurate measure of ground reaction force (GRF) magnitude, tibial acceleration (measured via tibial-IMU) is a reliable force surrogate and can identify changes in tibial load between fast bowling foot strikes (Callaghan et al., 2020). The utility of IMU as a wearable unit would provide a practical method of lower-limb assessment in fast bowling, allowing testing to be undertaken in more conventional, outdoor cricketing environments. The contents of this thesis were primarily made up of a literature review and two original research investigations that assessed the application of wearable devices in fast bowling intensity assessment.

Chapter Two of this thesis reviewed the current literature surrounding fast bowling external demand, injury, and intensity assessment. This chapter discussed the large physical cost placed on fast bowlers, the associations between acute-chronic activity loads and injury risk, and current methods of measuring intensity during fast bowling with wearable trunk devices. Whilst trunk devices provide reliable between-participant intensity data, those metrics cannot accurately represent the kinematics of the lower limbs (Panther & Bradshaw, 2013), where a large portion of fast bowler injury is reported (Davies et al., 2008). Large GRFs are commonly observed at the initial front-foot contact (FF1) of the delivery stride (Callaghan et al., 2020; Worthington et al., 2013a), and may be a contributing factor to low back injury (Bartlett et al., 1996). Whilst the magnitude of GRF at FF1 is established in the literature, no prior research had investigated the biomechanics of the fast bowling follow-through. This was despite other similar activities (golf swing, baseball pitching) reporting greater joint loads and muscular stress in the follow-through phases (Pappas et al., 1985; Steele et al., 2018). Furthermore, prior fast bowling research was limited to laboratory-based lower-limb assessments, using force platforms and three-dimensional motion analysis. Through this literature review, a clear gap in the research was apparent in the need to develop practical methods of fast bowling intensity quantification in outdoor environments. Based on research in similar sports, it seemed feasible that the follow-through foot strikes of the fast bowling delivery could also result in large GRFs that may also contribute to injury and as such, should be quantified in future cricket fast bowling research.

Chapter Three investigated the utility of tibia-IMUs and a trunk-GPS unit to classify prescribed bowling intensity efforts among 15 sub-elite fast bowlers. A principal component analysis (PCA) presented each wearable-device variable in separate components, conveying the importance of each in representing a unique aspect of the fast bowling data set. Importantly, foot strike accelerations were reported in separate components, demonstrating potential differences in tibial load across the delivery and follow-through strikes. Measures from the match and maximal-intensity conditions were significantly larger compared with the warm-up condition. No differences were observed between the match and maximal conditions. Given the PCA reporting of foot strike accelerations in separate components, and the utility of tibial-IMU in assessing bowling intensity, a further investigation as to the difference between the foot strikes was warranted.

Extending on the study in Chapter Three, Chapter Four compared the foot strike accelerations throughout the fast bowling delivery and follow-through. The foot strike at back foot re-contact (BF2) was found to have the greatest magnitude of acceleration, followed by FF1, front foot re-contact (FF2) and back foot initial contact (BF1). The greatest acceleration reported at BF2 potentially indicates this as the most forceful of the four measured foot strikes. This finding has immediate implications for fast bowling research, as the current focus surrounds the external loads of the delivery stride, particularly at FF1. Furthermore, tibial acceleration at FF2 was not significantly different from FF1, potentially representing similar GRFs at those foot strikes. Considerable magnitudes of tibial acceleration reported at BF2 and FF2 in Chapter Four demonstrate the importance of the follow-through stride during assessment of tibial load in the fast bowling delivery. Additionally, small correlations reported between the fast bowling foot strikes reinforces the unique contribution of each foot strike to the gross analysis of fast bowling intensity, and highlights the importance of the delivery and follow-through foot strikes when considering delivery intensity.

Overall, the findings of this thesis demonstrate a utility of both trunk- and tibia-mounted wearable devices to objectively classify fast bowling deliveries between warm-up and match, and warm-up and maximum delivery efforts. The ability to classify between bowling intensities using individualised data could assist coaches in monitoring external loads of fast bowlers and allow for the periodisation of training to appropriately prepare athletes for greater workloads. This thesis also conveyed the practicality of tibial-IMU to assess lower-limb kinematics in the outdoor cricket training setting. Peak tibial acceleration measures recorded at the delivery and follow-through foot strikes were found to represent unique aspects of the fast bowling workload. Furthermore, the BF2 strike in the fast bowling delivery produced the greatest resultant tibial acceleration. As such, it is possible that the BF2 strike is also the most forceful throughout the fast bowling delivery, and may be a significant contributor to lower back injuries in fast bowlers. This could have significant implications for further research, which has typically focused on tibial impacts at FF1 during fast bowling load assessment.

5.2 Direction for Future Research

Further research should extend on the knowledge that BF2 presents the greatest tibial accelerations and seek to confirm the magnitude of GRF at BF2, measured using a laboratory-based force platform. Prior cricket bowling research reports GRF of up to eight times body mass at FF1 (Portus et al., 2004), thus, a similar (if not greater) tibial load can be expected at BF2, based on the large tibial acceleration measures reported in this thesis. Similarly, Chapter Four showed that peak tibial acceleration at FF2 was not significantly different to FF1, so GRF at these foot strikes may be comparable. Evidence of considerable GRF at BF2 and FF2 would identify novel aspects of tibial load in the fast bowling delivery, which should consequently encourage researchers to involve follow-through assessment as part of routine fast bowling observations.

Additionally, future research should assess trunk and lower-limb kinematics between FF1 and BF2 to determine the potential cause of the large tibial acceleration reported at BF2. Prior research demonstrated the significance of lower limb and trunk angles, and subsequent centre of mass positioning, on GRF production at FF1 of the fast bowling delivery (Ferdinands et al., 2010; Worthington et al., 2013a). A similar assessment is warranted in the period between FF1 and BF2, where significant changes in centre of mass position could impact GRF development and tibial load at BF2. Rapid lateral trunk flexion and the large GRF spike at FF1 is postulated to contribute to lower back injury development (Bartlett et al., 1996). Hence, a detailed assessment of trunk positioning across the fast bowling delivery and follow-through foot strikes could become an important research consideration to identify injury-inducing events across the fast bowling technique.

The reliability of the delivery quantification methods demonstrated in Chapters 3 and 4 should also be assessed, to determine the replicability of those within-subject measures between-sessions.

Investigation of the ability for tibial-IMU to produce reliable force-surrogate estimates at both the delivery and follow-through foot strikes also warrants attention. Research has demonstrated an agreement between tibial-IMU force-surrogate measures and GRF, to estimate changes in tibial load at FF1 (Callaghan et al., 2020). However, the accuracy of tibial-IMU as a force-surrogate at the follow-through strikes remains unknown. An observed agreement between tibial-IMU and force platform GRF measures at BF2 would affirm BF2 as the most impactful foot strike and demonstrate a capability of tibial-IMU to monitor changes in tibial load across the delivery. This would have application to field-based fast bowling settings given the wearable nature of the IMU devices and allow for tibial load assessment during training.

While this research extends on previous laboratory-based research and applies it to the training setting, future fast bowling research should also incorporate tibial load assessment during competition. Wearable trunk units have become increasingly common for athlete load assessment in a variety of team field sports (including cricket), in both training and competition environments (Bliss et al., 2021; Cummins et al., 2013; Petersen et al., 2010). However, there is currently no published evidence demonstrating the application of tibial-IMU to assess fast bowling tibial loads in competitive settings. The ability to capture tibial-IMU data during competition could enable more accurate assessment of 'match intensity' outputs that would better-represent differences in intensity metrics between training and competition. This would enhance the specificity of athlete load monitoring across the duration of the season, providing coaches with more accurate intensity data to enable more evidence-based training prescription.

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Appendix – Ethics Approval

HEC20021 - New Application - Approved

humanethics@latrobe.edu.au <humanethics@latrobe.edu.au>
Tue 10/03/2020 1:58 PM
To: Kane Middleton <K.Middleton@latrobe.edu.au>
Cc: DANIEL EPIFANO <18936050@students.latrobe.edu.au>; Anthea Clarke <A.Clarke@latrobe.edu.au>; Sam Ryan <S.Ryan2@latrobe.edu.au>

** This is an automatically generated email, please do not reply. Contact details are listed below.**

Dear Kane Middleton,

The following project has been assessed as complying with the National Statement on Ethical Conduct in Human Research. I am pleased to advise that your project has been granted ethics approval and you may commence the study.

Application ID: HEC20021
Application Status/Committee: Science, Health & Engineering College Human Ethics Sub-Committee

Project Title: A novel method of assessing fast bowling intensity

Chief Investigator: Kane Middleton

Other Investigators: Daniel John Epifano, Sam Ryan, Anthea Clarke

Date of Approval: 10/03/2020
Date of Ethics Approval Expiry: 10/03/2025

The following standard conditions apply to your project:

- Limit of Approval. Approval is limited strictly to the research proposal as submitted in your application.

- Variation to Project. Any subsequent variations or modifications you wish to make to your project must be formally notified for approval in advance of these modifications being introduced into the project.

- Adverse Events. If any unforeseen or adverse events occur the Chief Investigator must notify the UHEC immediately. Any complaints about the project received by the researchers must also be referred immediately to the UHEC.

- Withdrawal of Project. If you decide to discontinue your research before its planned completion, you must inform the relevant committee and complete a Final Report form.

- Monitoring. All projects are subject to monitoring at any time by the University Human Ethics Committee.

- Annual Progress Reports. If your project continues for more than 12 months, you are required to submit a Progress Report annually, on or just prior to 12 February. The form is available on the Research Office website. Failure to submit a Progress Report will mean approval for this project will lapse.

- Auditing. An audit of the project may be conducted by members of the UHEC.

- Final Report. A Final Report (see above address) is required within six months of the completion of the project.

You may log in to ResearchMaster (https://rmenet.latrobe.edu.au) to view your application.

Should you require any further information, please contact the Human Research Ethics Team on:
T: +61 3 9479 1443| E: humanethics@latrobe.edu.au.

Warm regards,

Human Research Ethics Team
Ethics, Integrity & Biosafety, Research Office