

Cricket fast bowler monitoring and workload management

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This thesis is submitted in accordance with the requirements of The Graduate Research Office,
Australian Catholic University for the degree of Doctor of Philosophy by Dean McNamara.

October 2016

Declaration

This thesis contains no material published elsewhere or extracted in whole or in part from a thesis by which I have qualified for or been awarded another degree or diploma. No parts of this thesis have been submitted towards the award of any other degree or diploma in any other tertiary institution. No other person's work has been used without due acknowledgment in the main text of the thesis. All research procedures reported in the thesis received the approval of the relevant Ethics/Safety Committees (where required).



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Published Works by the Author Incorporated into the Thesis

The following is a description of the contribution of the main and co-authors for each of the published manuscripts supporting this thesis:

- 1) McNamara DJ, Gabbett TJ, Naughton G, Orchard J. How submarine and guided missile technology can help reduce injury and improve performance in cricket fast bowlers. *British Journal of Sports Medicine*. 2016. doi:10.1136/bjsports-2015-095935. Impact factor: 6.724

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Professor Geraldine Naughton	Assisted with conception of editorial Revision of manuscript	5%
Dr John Orchard	Assisted with conception of editorial Revision of manuscript	5%

- 2) McNamara DJ, Gabbett TJ, Naughton G. Assessment of workload and its effects on performance and injury in elite cricket fast bowlers. *Sports Medicine*, 2016, DOI 10.1007/s40279-016-0588-8. Impact factor: 5.579

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Professor Geraldine Naughton	Conceived systematic review and design Assisted data collection Analysed the data Revision of manuscript	10%

- 3) McNamara DJ, Gabbett TJ, Naughton G, Farhart P, and Chapman P. Physical preparation and competition workloads and fatigue responses of elite junior cricket players. *International Journal Sports Physiology Performance*, 2013, 8 (5), 517-526. Impact factor: 3.042

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- 4) McNamara DJ, Gabbett TJ, Chapman P, Naughton G, and Farhart P. The validity of microsensors to automatically detect bowling events and counts in cricket fast bowlers. *International Journal Sports Physiology Performance*, 2015, 10 (1), 71-75. Impact factor: 3.042

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- 5) McNamara DJ, Gabbett TJ, Chapman P, Naughton G, and Farhart P. Variability of PlayerLoad™, bowling velocity and performance execution in fast bowlers across repeated bowling spells. *International Journal Sports Physiology Performance*, 2015, 10 (8), 1009-1014. Impact factor: 3.042

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I hereby declare that my contribution to each of the four published/submitted manuscripts, as outlined above, to be accurate and true.

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Acknowledgements

I would like to express my sincere thanks to my supervisor, Associate Professor Tim Gabbett. Your honest and challenging advice, coupled with the knowledge that you are entirely in support of me has been undoubtedly the biggest factor in completing this thesis. Thank you for your guidance throughout this large part of my life.

To my co-supervisor, Professor Geraldine Naughton. I would never have undertaken this PhD without your encouragement and confidence. Your advice, support, guidance and nurturing not only makes better students, but better people. Thank you for sharing this gift.

To Paul Chapman, Patrick Farhart, Murray Ryan and those at Cricket NSW and Cricket Australia, thank you for your time, expertise and support throughout this entire process.

Thanks to my colleagues at SSEP, particularly Chris Pappas, for giving me the time, space and patience to complete this thesis.

Lastly, thank you to my family. My parents for your constant support of any challenges or goals that I want to achieve. Finally, thanks to my beautiful wife Karen. I don't know anyone else in the world who could give so much patience and support to something they still know nothing about! I love you very much.

Love the work, not the idea

Abstract

The sport of cricket is challenged by three formats of the game; each with varying workload demands. The most recent format is T20 cricket, first played internationally in 2005. Further to this, elite performers are often required to play for upwards of four different professional teams across the year; increasing the complexities in player workload management and other sports science-related support.

Fast bowlers have greater overall match-play demands than other playing positions in cricket. Wearable microtechnology for tracking external load in athletes is common practice. Despite microtechnology enabling meaningful analyses of workload beyond routinely reported metrics, little application has occurred within fast bowling.

The high injury risk in fast bowlers is well established, yet the intensive demands on these athletes remain poorly understood. The overall aim of this program of research was to use scientific literature to first understand the interaction of workload, injury and performance in elite level fast bowlers and then improve the understanding of workload management using advances in wearable microtechnology. The program of research in this thesis “*with publication*” first generated studies identifying the problem (a systematic review). The four subsequent chapters of original research built on the review to profile the match-play and training demands of cricketers, explore the variability of wearable microtechnology outputs during fast bowling, and finally develop and quantify an innovative means to monitor and manage workload within the specific demands of fast bowling in cricket.

Although monitoring acute and chronic workloads of fast bowlers remains the most ideal method for identifying preparedness and injury likelihood in fast bowlers, complexities exist that make the systematic prescription of bowling workloads difficult. The results confirmed that the external load of cricket match-play and training varied between fast bowlers and non-

fast bowlers. Furthermore, external loads experienced by 26 elite performing cricketers differentially affected the neuromuscular, endocrine, and perceptual fatigue responses of these players.

Outputs from wearable microtechnology provided adequate stability across the performance of elite fast bowlers. These outputs were comparable with routinely used measures of fast bowling performance and intensity. Algorithms linking microtechnology outputs demonstrated good sensitivity in detecting fast bowling events in elite cricketers across competition (99.5%) and training (99.0%). The specificity of detecting fast bowling events decreased in competition (74.0%) however, remained high during training (98.1%). With the ability to automatically detect fast bowling events, metrics of bowling intensity can be explored more rigorously. Outputs from the gyroscope and accelerometers in the wearable technology provided strong associations with prescribed bowling intensity.

Collectively, this thesis has highlighted the challenges of applied research in cricket, and more specifically the capacity to more objectively monitor external load in cricket fast bowlers. Wearable microtechnology has the potential to advance and refine measures of bowling workload and provide a greater depth of support for cricket fast bowlers.

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List of Abbreviations

#	Count
#/min	Counts per minute
Acc	Acceleration
ANOVA	One -way analysis of variance
au	Arbitrary units
au/min	Arbitrary units per minute
BBL	Big bash league
CI	Confidence Interval
<i>Cd</i>	Cliff's Delta
cm	Centimetre
CMJ	Countermovement jump
CMJRelP	Countermovement jump relative power
CMJFTime	Countermovement jump flight time
CV	Coefficient of variation
<i>d</i>	Cohen's effect size statistic
ES	Effect size
FB	Fast bowler
GPS	Global positioning system
IPL	Indian premier league
Kg	Kilogram
Km/h	Kilometres per hour
min	Minute
m.min	Metres per minute
m.s ⁻¹	Metres per second (velocity)
m.s ⁻²	Metres per second (acceleration)

mmol.L ⁻¹	Millimoles per litre
n	Number
Non	Non-fast bowler
PEDro	Physiotherapy evidence database
r	Correlation
RPE	Rate of perceived exertion
ROM	Range of motion
s	Seconds
SD	Standard Deviation
SWC	Smallest worthwhile change
T20	Twenty over cricket match

Navigation of the Thesis

Workload monitoring in fast bowlers is established as important for both injury reduction and fast bowling performance. This thesis addressed fast bowling workload by first identifying the problem and, second by applying research innovation to fast bowling workload management.

Chapters 2 and 3 within this thesis *identify the problem* through the rigor of a systematic review and observational study investigating the fatigue responses of cricket workload across all playing types in both preparation and competition periods. These preliminary chapters introduce the challenges of measuring workload in cricket fast bowlers. The research presented in chapters 2 and 3 also established that variation in workload across cricket playing positions existed and that these workloads resulted in different fatigue outcomes across position types.

The second part of this thesis investigated the use of wearable microtechnology in the advancement of fast bowling workload monitoring. The aim of these chapters was to establish new methods and approaches for quantifying the workload of cricket fast bowlers. The first study investigated the accuracy of wearable microtechnology to detect fast bowling events in both training and competition. It was established that wearable microtechnology was able to detect fast bowling events. With the automated detection of fast bowling events possible, the next two studies explored the meaningfulness of the parameters provided from the wearable microtechnology. This was completed in two parts, firstly establishing that the outputs had adequate stability across fast bowlers and bowling spells and secondly, establishing a relationship between bowling intensity and microtechnology outputs.

Chapter 1: General Introduction

1.1 Overview of Cricket – Historical Context

The team sport of cricket originates from England and has spread internationally throughout the British Commonwealth. Comprising two teams of 11 players, specific positional roles can be classified into various sub-categories including batsmen, bowlers (sub-categories fast, medium, spin) and fielders (sub-categories wicket-keepers, inner and outer). Finer classifications within these sub-categories can also be identified. While each player has a specific role within a team, all players are required to field throughout the course of a game. The first international match was played in 1844 between the USA and Canada, while England's first international tour was to North America in 1859 and was followed by tours to Australia in 1862. Follow-up tours between England and Australia eventually lead to the first Ashes series in 1882; a competition still played today. Domestic cricket competitions originated in England and Australia between 1890 and 1892 to coincide with international competition.

Cricket match-play largely remained consistent until 1971 when the first international limited overs game was played in Melbourne, Australia. Limited overs cricket had gained popularity during the 1960s when established in England. Limited overs cricket, also referred to as one-day cricket, is distinguished by the limited number of overs in each innings, along with regulations and rules on individual bowling workloads (10-overs). This differs from multi-day cricket that is unlimited in the overs of each innings, and the overs bowlers can bowl in each innings. With the popularity of limited overs cricket increasing, the cricket World Cup was introduced in 1975, using a limited overs format (50-overs per innings).

The evolution of cricket match-play has continued more recently with the introduction of 20 over cricket (Twenty20, T20). This again, is a shorter format of limited overs cricket, allocating a maximum of 20-overs in each batting innings and further reduction in the bowling restrictions for each bowler (4-overs). T20 cricket originated in England in 2003, with the first international game in 2005. The first T20 World Cup was played in 2007.

1.2 Identifying the Problem

Both the fitness and fatigue from training and competition are directly linked to athletic performance. The manner in which fatigue influences sporting performance has received considerable attention. Understanding both acute and chronic fatigue is vital in athlete management; an issue of current interest in applied team sport research [1-4]. A thorough understanding of fatigue and how it manifests is vital in team sports, where improving performance outcomes is critical.

Researchers have previously modelled the relationship between training and performance [5-7]. Performance outcomes from training are directly related to the magnitude of both the fitness and fatigue responses to a given workload, and the time decay of each of these two components [8]. This “Fitness-Fatigue” model suggests performance (fitness) is proportionally more influenced by the negative (fatigue) than positive responses. However, the time attenuation of fitness is considerably longer in duration than fatigue [9]. Subsequently, adequate recovery is required for improved athletic performance and to minimize the likelihood of overtraining syndrome. While this model is relatively simple in design, measurement and assessment of each component are relatively complex and influenced by factors in addition to, and other than, training load and intensity [10]. In particular, the fatigue component of the model has been

identified as considerably complex and multidimensional. Currently, exercise induced fatigue has no accurate clear marker or measure [11]. If overreaching repeatedly occurs, chronic maladaptation may potentially result in overtraining syndrome. Overtraining syndrome is characterised not only by a reduction in athletic performance, but also compromised neuromuscular, hormonal and biological status [12]. For the purpose of this thesis, a reduction in neuromuscular, hormonal and/or biological status will indicate that athletic performance may be compromised.

While fatigue and over-training have been studied in athletes from individual sports [5, 13], and more recently athletes from high intensity, intermittent team sports [14, 1], no research has specifically investigated overreaching or over-training in fast bowlers or other cricketers. However, acute physiological responses have been studied in fast bowlers performing repeated fast bowling spells [15]. No significant physiological changes and only small reductions in bowling velocity were observed between bowling spells separated by 45 minutes [15]. While this study provided important information on the physiological and performance outcomes associated with repeated fast bowling spells, the 45-minute recovery period provided between bowling spells potentially neglected to account for the varying recovery opportunities in each competition format.

As with most team sports, cricket has requirements specific to particular player types. These requirements are associated with various physical loads and consequently require specific preparation and skill. Often fast bowlers are required to perform most of the team bowling workload during cricket competition.

In addition to increasing fast bowling workloads over the cricket calendar, the recent introduction of 20-over cricket has augmented the types of injuries being sustained by elite cricketers [16]. Thigh and hamstring injury incidence increased between 2007 and 2009, around the time that 20-over cricket became prominent in the cricket calendar. The marked injury increase is suggestive of the changing physical demands of cricket [16]. These 20-over cricket competitions have seen professional cricketers contracted to numerous professional teams across the world, which complicates the management of athlete well-being [16]. Reliable and cricket-specific measures of fatigue and workload will assist coaches during periods in which conditioning staff and coaches have limited access to their athletes.

1.3 Research Innovation

Workload monitoring can play an important role in preventing overtraining syndrome and management of unwanted amounts of fatigue. Both generic and sport-specific measures of workloads are used in sport. Workloads can be regarded as external and internal. External load comprises the ‘work’ performed in a physical task, while internal load describes the physiological or psychological response (i.e. ‘strain’) of the athlete to the external work performed. Examples of external loads include balls bowled in cricket [17], tackles in rugby league [18] and distance run in Australian Football [19]. Examples of internal load include heart rate and ratings of perceived effort.

Fast bowling workloads are linked to injury risk [21, 21]. A dual workload threshold has been shown to influence injury risk in elite fast bowlers [20], whereby both under- and over-bowling increased the risk of injury. These findings suggest that a minimum volume of bowling is required to increase injury resilience, while excessive bowling loads may increase injury risk.

Despite the accepted association between fast bowling workloads and injury risk, recent cricket workloads at the elite level have been significantly altered by the introduction of 20-over cricket. Arguably, this may have resulted in under-bowling in some circumstances and over-bowling in others [20]. More specifically, the introduction of 20-over competitions into international and domestic cricket schedules have increased total load over the cricket calendar [16]. However, it is also likely that limited over competitions may provide inadequate workloads to prepare fast bowlers for multi-day cricket, particularly when short turnaround between competitions exists. Workloads in fast bowlers may need to be gradually and systematically increased in order to prevent injury, particularly as a link has been shown between increased acute bowling workloads and a 3-4 week delayed increase in injury risk [22].

The use of wearable technology to determine a measure of workload is not a new concept. Wearable technology such as pedometers have for several years, been used to track simple workloads such as steps walked [23]. Currently, many elite level sporting teams and individuals use microtechnology devices to monitor external workload [18, 24, 25]. Microtechnology manufacturers also use accelerometers and gyroscopes housed within commercially available global positioning system (GPS) devices to provide additional information on external loads [25-28]. These systems are adding alternative measures of workload to that provided by GPS technology alone, including Player Load™ which is derived from the tri-axial accelerometers housed within the microtechnology device [24]. The multiple measurement options within the wearable microtechnology may provide a reliable tool for detecting fast bowling events and provide insight into the workload and intensity of the fast bowling loads that are contributing to injury or impair optimal performance in elite fast bowlers.

Therefore, this thesis argues the need to monitor the increasing demand of fast bowlers; as a sub-group of athletes particularly vulnerable to injury and fundamental to team success. Strengthening the evidence base around objective and multiple measures of workload will improve the confidence around understanding the (i) demands of fast bowling and (ii) workload management of players. To this end, innovations within microtechnology require sport-specific adaptations for optimal use in cricket.

To address this rationale, a number of experimental hypotheses were proposed in this program of research:

- (i)* Limited scientific data on workload and fast bowling performance will be present since the introduction of T20 cricket.
- (ii)* Training and competition demands of fast bowlers will be higher than non-fast bowlers.
- (iii)* Wearable microtechnology will be both sensitive and specific for the detection of fast bowling events during training and match-play.
- (iv)* Outputs from wearable microtechnology will provide adequate reliability across repeated bowling events.
- (v)* Wearable microtechnology will be sensitive to distinguish the intensity of a prescribed fast bowling event.

The sequence of studies designed to investigate the hypotheses are as follows:

Cricket fast bowler monitoring and workload management

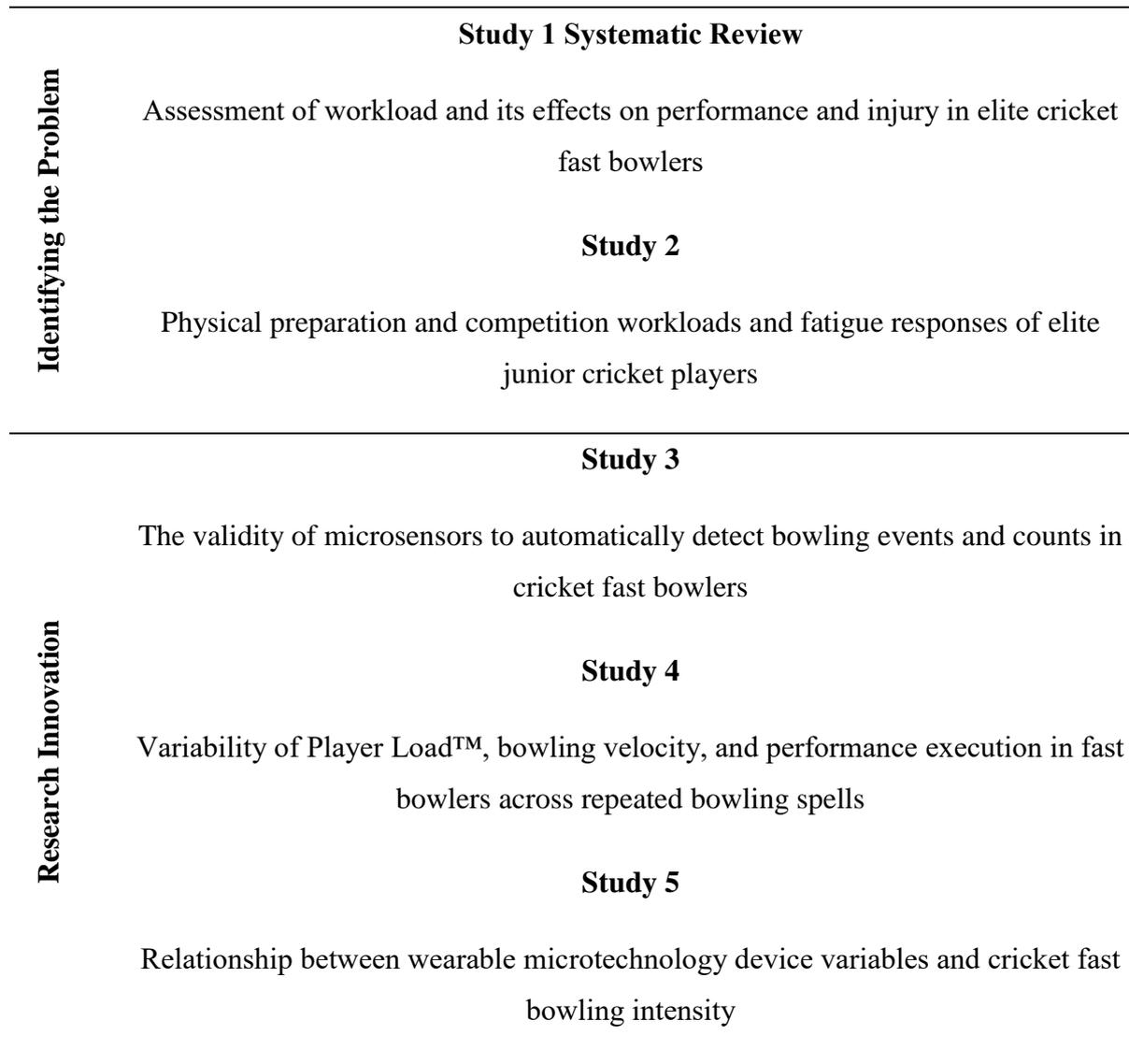


Figure 1. Workflow of thesis.

**Chapter 2: Assessment of workload and its effects on performance and injury in elite
cricket fast bowlers: a systematic review**

This study has been accepted for publication following peer review. Full reference details are:

McNamara DJ, Gabbett TJ, Naughton G. Assessment of workload and its effects on performance and injury in elite cricket fast bowlers. *Sports Medicine*, 2016, DOI 10.1007/s40279-016-0588-8.

2.1 Abstract

Cricket is distinctly positioned in the world of elite sports because three different formats now exist; each with characteristically different workload requirements. Fast bowlers have greater match-play workload requirements and are at greater injury risk than other positions. An update on the current cricket literature regarding fast bowling match-play physiology, workload and injury is required to demonstrate the extent to which workload is related to performance and injury in elite fast bowlers since the introduction of 20-over cricket in 2005. The current review examined articles published in English with data collected from 2005 onwards pertaining to in situ cricket fast bowling physiology, match-play, injury, and workload. Across four databases the following search terms were searched using the combinations of the following key words: ‘cricket’ and ‘bowl’; inclusive of ‘pace’; ‘fast’; ‘medium’; or ‘seam’ bowling. Articles from 2005 onwards, with male participants, high performing or elite, and fast bowlers in the game of cricket were considered for inclusion. Only workload assessments captured in a field setting were included. A total of 751 articles were identified. Exclusions included 527 duplicates, pre 2005, review articles or abstracts. A further 185 articles were excluded after review of titles and abstracts that were deemed to be outside the scope of research or population. Full texts from 39 articles were reviewed, with only 17 included in this systematic review. In five articles reviewed, fast bowlers had a greater workload than other player types. Bowling workload history was reviewed in seven articles and appeared to have a complex interaction with likelihood of injury and injury type. Fast bowling workload has a well-recognised relationship with injury and performance. Although monitoring acute and chronic workloads of fast bowlers remains the most ideal method for identifying preparedness and injury likelihood in fast bowlers, complexities exist which make the systematic prescription of bowling workloads difficult. Advances in technology to monitor workloads may provide further insight into the intensity and workloads of fast bowlers.

PROSPERO Registration number: CRD42015032466

2.1.1 Key Points

- Although elite fast bowlers are generally adequately prepared for the acute workloads required for cricket match-play, large ‘spikes’ in acute workloads can manifest as delayed injury risk.
- Twenty20 cricket complicates workload monitoring, injury management and physical preparation in cricket.
- Interaction between advances in athlete tracking systems and longitudinal injury research is required to advance the understanding of fast bowling management.

2.2 Introduction

Over the past 20 years of cricket, Test and 50-over matches have largely dominated international competition. Along with the first T20 international in 2005, the first T20 domestic competitions started in Australia, England, New Zealand and South Africa. The remaining test playing nations began their T20 domestic competitions in 2006. These domestic competitions evolved into two of the largest ‘domestic’ cricket competitions: the Indian Premier League (IPL) in 2008 and the Big Bash League (BBL) in Australia in 2011. Increased competitions marked a major change across international cricket as the teams within each competition functioned as individual franchises, with the ability to buy and trade players from across the world (Figures 2 and 3). Large financial incentives became available for elite cricketers from franchise-based competitions; resulting in some cricketers adding intensely demanding competitions to their yearly schedule or specialising solely in T20 cricket. This diversity in cricket training demands and match-play, particularly with the introduction of T20 cricket, potentially challenges the literature published in the years prior to 2005, when T20 cricket originated.

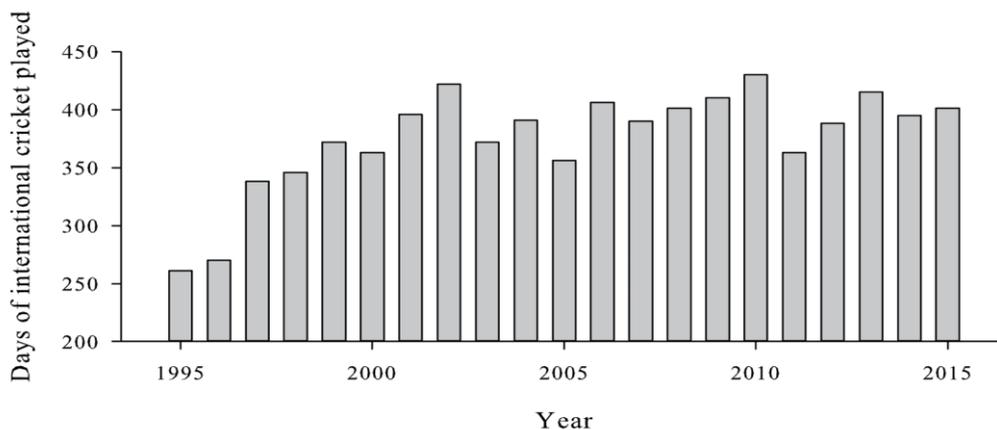


Figure 2. Number of days of international cricket played over the last 20 years [29].

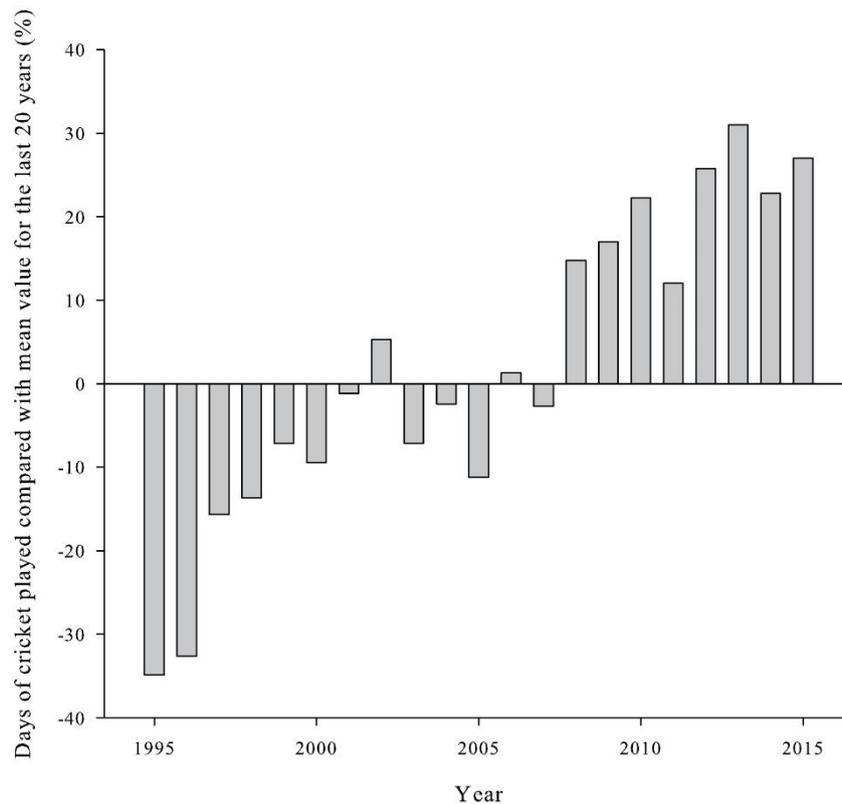


Figure 3. Days of cricket played (internationals, IPL, BBL) compared with mean value for the last 20 years [29]. IPL = Indian Premier League. BBL = Big Bash League.

As with most team sports, cricket has requirements specific to particular playing roles. These requirements are associated with various physical loads and consequently specific preparation and skills are needed [30]. Fast bowling workloads are linked to injury risk [20, 22]. A dual workload threshold has been shown to influence injury risk in elite fast bowlers [20], in which both under- and over-bowling performances increase the risk of injury. These findings suggest a minimum volume of bowling is required to increase injury resilience, while excessive bowling loads may increase injury risk. Despite accepted associations between fast bowling workloads and injury risk, recent cricket workloads at the elite level have been significantly altered by the introduction of 20-over cricket. Arguably, this may have resulted in under-

bowling in some circumstances and over-bowling in others [16]. Workloads for fast bowlers may need to be gradually and systematically increased in order to prevent injury, particularly as a link has been shown between increased acute bowling workloads and both a 7 day delayed [21] and 3-4 week delayed [22] increase in injury risk. In addition to increasing fast bowling workloads over the cricket calendar, the recent introduction of 20-over cricket has influenced the types of injuries sustained by elite cricketers [16]. Thigh and hamstring injury incidence have increased in the era of 20-over cricket. The marked injury increase is suggestive of the changing physical demands of cricket and condensed cricket scheduling [31].

The current environment of professional cricketers contracted to numerous professional teams across the world, complicates the management of athlete workloads and monitoring of well-being [16]. Reliable and cricket-specific measures of fatigue and workload may assist coaches during periods in which conditioning staff and coaches have limited access to their athletes. The demands of match-play in elite sport frequently change as a result of both competition strategy and professionalism. Speculatively, no other professional sport has experienced greater changes in competitive workload demands than cricket over the past 10 years, since the introduction of T20 cricket.

Like many sports, cricket preparation requires a balance between appropriate workloads to elicit improvements in performance and injury resilience, and adequate recovery to prevent injury and overtraining which compromise performance. Fast bowling performance is characterised by both accuracy and ball velocity. Fatigue and inadequate preparation have the potential to compromise both technique and force development, both of which will impact ball velocity and accuracy and subsequent performance. The authors of this systematic review are

aware of a recently published systematic review regarding factors associated with non-contact injuries in adult fast bowlers [32]. This review will distinguish itself from the recent systematic review with a primary aim of demonstrating the extent to which workload is related to injury and/or performance in elite cricket fast bowlers using observational and cross-sectional studies. Secondary aims were first, to provide an update of the physical requirements of elite fast bowlers since the introduction of T20 cricket, and second, to provide an update on the measures of workload within cricket fast bowling.

2.3 Methods

This review has been registered with PROSPERO.

(http://www.crd.york.ac.uk/PROSPERO/display_record.asp?ID=CRD42015032466).

2.3.1 Search Strategy

Articles for this review were systematically identified through the search of the electronic academic databases SPORTDiscus, MEDLINE, Scopus and Web of Science. These databases were searched using the combinations of the following two major key terms in the title and abstract: (1) 'cricket' and (2) 'bowl'; with the following terms of 'pace' 'fast', 'medium' and 'seam' connected to 'bowl' using 'OR'. These major two search categories were combined using 'AND'. To remain contemporary, the search was restricted to full-length peer-reviewed articles written in English after 2005 through to April 2015. All full length papers were searched for additional references not identified in the initial search.

2.3.2 Selection Criteria

Duplicate articles were removed after an initial search was performed. All papers published or using data prior to 2005 were excluded from further review. The independent reviewers (DJM, TJG, and GN) then screened each paper for relevance based on the inclusion and exclusion criteria. The inclusion criteria for this review were articles published with data from 2005 onwards – the year of the first international T20 match, with male participants, high performing or elite, and fast bowlers in the game of cricket. Data needed to be collected in situ, i.e. in the field, not a laboratory. To be included, articles were required to provide data on injuries, fast bowling performance, cricket workload or measures of cricket workload. Articles were excluded if they were case studies, abstracts, review articles, published in a language other than English or non-peer reviewed articles. Disagreements between the independent reviewers regarding article inclusion or exclusion were discussed and resolved.

2.3.3 Data Extraction

Data extracted included the year and country of publication, the nature of participants, key dependent variables and study design, statistical treatment, major results, key outcomes and limitations. Reporting of outcomes included odds ratios, relative risk, means and confidence intervals (CI) and effect sizes (ES).

2.3.4 Evaluation of the Quality of Reporting in Reviewed Studies

Evaluating the quality of reported literature required a modified scale used in a previously published review [33]. The previous instrument for evaluating quality reporting was derived from the Delphi [34], Physiotherapy Evidence Database (PEDro) [35], and Cochrane scales

[36], and was described as more specific to applied strength and conditioning study designs and reported protocols. None of the reviewed studies involved random sampling; limiting the application of the above mentioned scales in this review. Purposive sampling was the more dominant recruitment strategy in the reviewed studies due to the small number of athletes meeting the inclusion criteria as elite fast bowling cricketers. Also, due to the observational nature of research on elite populations (not typically involving more than the one group of interest), modifications to the composite quality scale were required for this review. Subsequently for this review, an 8-item scale (range 0 – 16) was used to assess the quality of reporting. The eight criteria were scored as: 0 = clearly no; 1 = maybe; and 2 = clearly yes. The criteria included:

1. inclusion criteria were clearly stated;
2. clear definitions of intervention/protocols and or procedures were provided;
3. groups were tested for similarity or the single group was well described;
4. outcome variables were clearly defined;
5. assessments were practically useful;
6. duration of intervention was practically useful;
7. statistical analysis was appropriate;
8. point measures of variability were evident. Quality reporting was ranked independently, then disagreements on scores were discussed to a point of consensus among the authors.

2.4 Results

The flow diagram in figure 4 shows the number of papers found, excluded (with reasons) and included. A total of 751 studies were initially retrieved from the four databases. Thirty-nine studies were reviewed in full and a further 23 articles were excluded for reasons including: outside the scope of research (n = 15), abstract only (n = 3), population (n = 1), entire data collection pre 2005 (n = 3), and not peer reviewed (n = 1). The remaining 16 articles were included in the systematic review. A further article was included after being located by another source. In total, 17 articles were included in the systematic review.

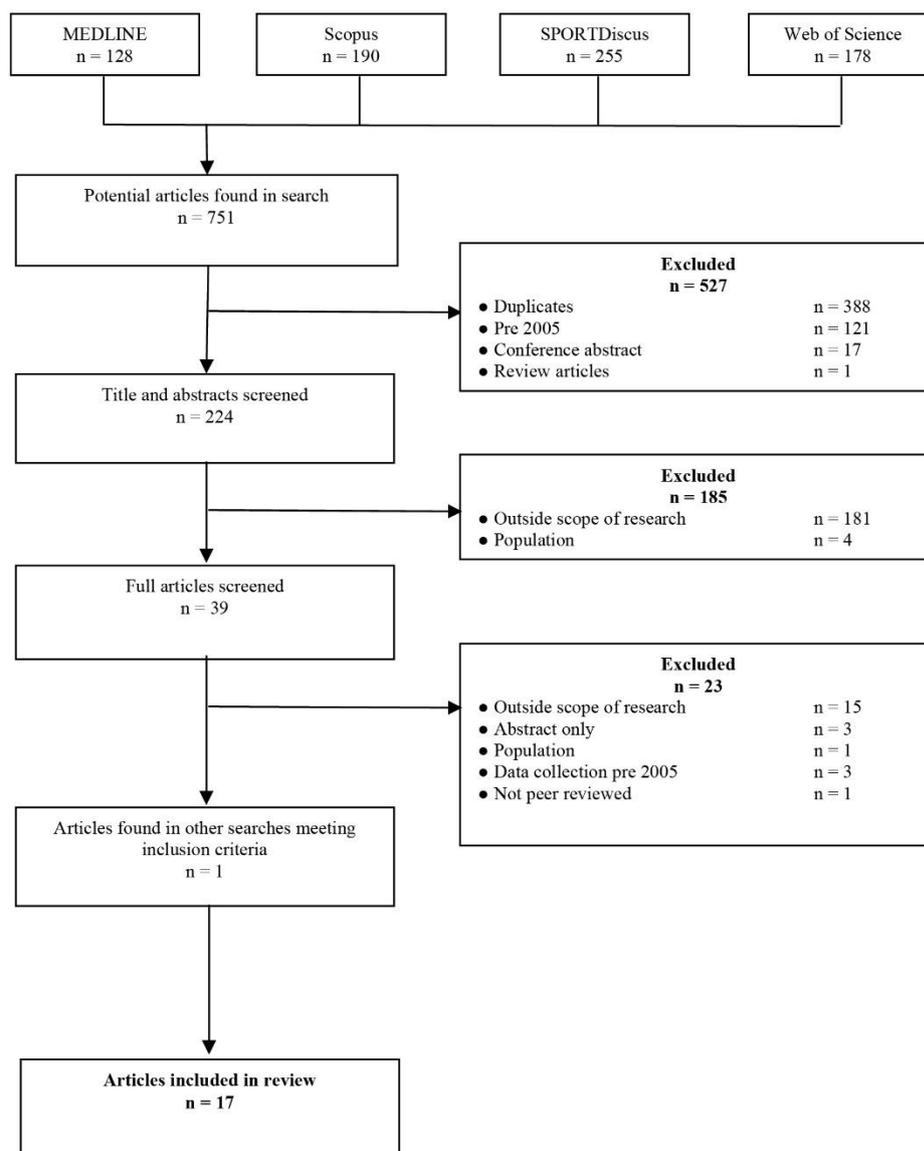


Figure 4. Flow chart of study selection.

Table 1. Summary of studies included in the systematic review.

Study	Nationality	Participants (n)	Level of Competition	Variables	Methods	Statistics	Results	Limitations	Quality (score, %)
Pyne et al. (2006) [37]	Australian	72	24 first class Australian cricketers. 48 Australian junior representative players	Bowling performance; ball velocity in bowling. Anthropometric measures; height, mass, skinfolds, body composition estimates. Strength testing; single leg jumps and bar throw tests.	Senior and junior fast bowlers were profiled in bowling performance, anthropometric measures and strength measures. Data were observed as a comparison between both groups and as a predictor of bowling performance (ball velocity) within each age group.	Cohen's ES statistic for differences between senior and junior cricketers. Correlation coefficient for association between bowling velocity and anthropometric/strength variables.	Senior fast bowlers had greater ball velocity, muscle mass and bench press throw. The best predictors for ball velocity in senior fast bowlers were static jumping and arm length. The best predictors for ball velocity in junior fast bowlers were static jump, bench throw, body mass, % body mass and height.	Variability in 1-legged CMJ protocol.	15, 94%
Duffield et al. (2009) [15]	Australian	6	First class Australian cricketers.	Body mass. Heart rate. Core temperature. Capillary blood lactate, pH, and glucose. Perceptual measures or RPE and muscle soreness. Repeated vertical jump efforts.	Initial measures of repeated sprint ability and peak bowling speed were taken. A second session of 2 x 6-over bowling spells was completed to measure bowling performance (speed and accuracy) and run-up speed. Dependent variables were assessed during the repeated bowling spells.	A one-way, repeated measures ANOVA was performed to determine differences between bowling spells. Cohen's effect size statistic was used to determine practical importance of change. Pearson's correlation coefficient was used to determine the association between measures.	No decrement in bowling velocity and accuracy across repeated bowling spells. No differences in heart rate, core temperature, lactate, pH, glucose, RPE, muscle soreness and vertical jump across repeated bowling spells.	Limited to training environment.	15, 94%
Orchard et al. (2009) [22]	Australian	129	Professional cricketers across Australia.	Injury: acute noncontact or a gradual-onset bowling mechanism.	Prospective cohort study over 10 years of injury history in Australian fast bowlers. The study compared future injury risk in bowlers of high and low workload status.	t tests to compare the number of overs bowled. Risk ratios were calculated to compare high and low workload groups. CIs were calculated using Taylor series expansions.	Bowlers who performed > 50 overs in a match had a significantly increased injury incidence in the next 21 days compared with those bowlers who bowled < 50 overs. Bowlers who bowled > 30 overs in the second inning of a match had a significantly increased injury risk per over bowled in the next 28 days	Irregular scheduling of match-play. Definition of overuse injury.	13, 81%

Table 1. Continued

Study	Nationality	No. of Participants	Level of Competition	Key Dependent Variable	Methods	Statistics	Results	Limitations	Quality (score, %)
Johnstone et al. (2010) [38]	United Kingdom	15	Professional cricketers from the English first class county competition.	Anthropometric data, aerobic fitness testing (multistage fitness test), flexibility (sit and reach test), speed (quick single, run 'a' 3), strength (medicine ball throw, press ups, jump testing).	A cross-sectional design was used to profile the physical and athletic profiles of professional cricketers. Participants were classified as either a batsman or a bowler for comparison.	Descriptive results expressed as mean \pm SD and 95% CI. Magnitude of difference interpreted using Cohen's ES. ES thresholds: 0.2 - 0.6 (small), 0.6 - 1.2 (moderate), 1.2 - 2.0 (large), >2.0 (very large).	Small to moderate effects were observed across all variables except for medicine ball throw and press up tests which showed large effect sizes.	Sample sizes were limited to 9 bowlers and 6 batsmen. Reliability and validity of field based testing.	11, 69%
Orchard et al. (2010) [39]	Australian	205	Australian first class fast bowlers	Injury (excluding lumbar stress fracture)	Prospective cohort risk factor study from data collected between 1998 and 2009. Risk ratios were calculated to compare the seasonal incidence of various injuries between bowlers with a prior history of lumbar stress fracture and those with no history of lumbar stress fracture.	Two-by-two χ^2 test. A risk ratio was calculated for each injury category. CIs were calculated using Taylor Series expansions	Risk of calf strain was strongly associated with prior lumbar stress fracture injury history.	Survey records may have missing data from injuries that occurred prior to data collection. Players may have had asymptomatic pars defects that went undetected.	13, 81%
Orchard et al. (2010) [16]	Australian	Not stated	Australian first class cricketers	Injury	Researchers compared injury rates from 1998 to 2009. The researchers suggested injury rates should be expressed relative to days of play rather than hours of play as cricket is uniquely positioned in that it has 3 variations of match-play.	Not stated	When expressing injury rates relative to days of play, injury rates normalised for T20 cricket.		7, 44%
Petersen et al. (2010) [40]	Australian	42	Domestic and international elite cricketers from 4 countries.	Movement patterns measured with GPS technology. (walk, jog, run, stride, and sprint)	Participants were fitted with a GPS unit worn during cricket match-play (T20, 50-over, and multi day cricket). Analysis of movement was classified as standing/walking, jogging, running, striding, and sprinting.	Magnitude-based inferences used to establish differences between player types. CV% was used to measure variability.	Fast bowlers performed the greatest workload per hour of match-play across all match-play types. One day and T20 cricket required 50-100% more sprinting per hour than multi-day cricket.	Only one multi-day game was analysed.	15, 94%

Table 1. Continued

Study	Nationality	No. of Participants	Level of Competition	Key Dependent Variable	Methods	Statistics	Results	Limitations	Quality (score, %)
Petersen et al. (2011) [41]	Australian	42	National level cricketers	GPS movement analysis. Heart rate. Blood lactate.	Training activities were classified into conditioning, skill, and game simulated sessions. GPS movement analysis was completed for each training session. Movement analysis was compared across training and previously published match data.	ES statistics were used to quantify the difference between training sessions. CV% was used to measure variability in time-motion data.	Conditioning drills had greater duration when compared to skill sessions. Conditioning sessions had greater intensity than both skill sessions and game simulated sessions.	Variability in high intensity efforts.	15, 94%
Petersen et al. (2011) [42]	Australian	54	Australian international and state level cricketers	Movement patterns measured with GPS technology. (walk, jog, run, stride, and sprint)	Participants were fitted with a GPS unit worn during cricket match-play (14x international 50-over, 3x test matches, 6x state level 50-over matches, and 5x state level multi-day matches). Analysis of movement was classified as standing/walking, jogging, running, striding, and sprinting.	ES statistics were used to quantify the difference between game formats and competition level. CV% was used to measure variability in time-motion data.	50-over cricket (compared to multi-day) and test matches (compared to state level competition) required more high-intensity running.	Limited number of test fast bowlers willing to wear the GPS device during competition.	14, 88%
Lombard et al. (2012) [43]	South African	10	Elite South African fast bowlers.	CK. Visual analogue scale muscle pain ratings. ROM and isometric maximal strength testing.	Physiological measures were assessed as a baseline followed by 2 days of rest and a bowling day which included 8overs of bowling at match intensity. Physiological measures were than assessed the day following the 8overs of bowling.	ANOVA. Post hoc testing was performed using Tukey's multiple comparison test.	CK and muscle pain were elevated 1hour and 24 hours post bowling. No change was observed in maximal isometric strength. Ankle ROM was reduced at 24 hours post bowling.	Indoor bowling surface may not reflect match requirements.	10, 63%
Phillips et al. (2012) [44]	Australian	32	Australian national, elite emerging and junior fast bowlers.	Ball velocity. Bowling accuracy.	Bowlers were required to bowl 30 balls at varying lengths to targets. Bowling measures of accuracy and velocity were recorded.	Effects of skill level and delivery type on each accuracy measure were assessed independently using a multiple mixed design ANOVA with repeated measures. Post hoc multiple comparisons were performed using Bonferroni corrected t-tests. Pearson's product moment correlation coefficient was used to find relationships between consistency, accuracy and velocity.	Elite fast bowlers performed better in speed and accuracy. National and emerging fast bowlers were able to adapt to varying bowling length changes within the same session.	Potential overlap in skill level in developmental groups.	12, 75%

Table 1. Continued

Study	Nationality	No. of Participants	Level of Competition	Key Dependent Variable	Methods	Statistics	Results	Limitations	Quality (score, %)
McNamara et al. (2013) [30]	Australian	26	National level under 19s and 17s cricketers.	Movement patterns measured with GPS technology. Endocrine markers (cortisol and testosterone). Perceptual well-being. Neuromuscular function.	Fast bowlers and non-fast bowlers were assessed over a 7 week preparation period and 10 day competition period.	ES statistics were used to analyse differences between groups in endocrine, perceptual well-being and neuromuscular function measures. Non-parametric ES statistics were used for movement patterns.	Fast bowlers had greater competition and preparation workloads. Endocrine markers suggested that fast bowlers were in a more catabolic state during both preparation and competition, whilst perceptual well-being was lower in non-fast bowlers.	Lack of control of physical activity outside structured training sessions.	14, 88%
Ranson et al. (2013) [45]	United Kingdom	76	International cricketers performing in the Cricket World Cup.	Time loss injury. Non-time loss injury.	Time loss and non-time loss injuries sustained during the 2011 Cricket World Cup were recorded by medical staff.	Not Stated	23 time-loss and 97 non-time-loss injuries were recorded across 5 teams in the 2011 Cricket World Cup		10, 63%
Hulin et al. (2014) [21]	Australian	28	Elite Australian fast bowlers	Session RPE. Non-contact injury resulting in loss of match-time or training session.	Data were collected over a 6-year period. Workloads were the total number of balls bowled per week (external workload) and the session RPE (internal workload). One-week data (acute workload), together with 4 week rolling average data (chronic workload), were calculated for external and internal workloads. Training-stress balance was assessed as negative or positive based on acute and chronic workloads.	The likelihood of sustaining injury was analysed using a logistic regression model.	Findings demonstrated that larger increases in acute workloads were associated with increased injury risk in elite cricket fast bowlers.		14, 88%
McNamara et al. (2015) [46]	Australian	12	Elite national and international Australian fast bowlers	Automated bowling detection from GPS/microtechnology unit	Participants performed a series of bowling, throwing and fielding activities. Sensitivity and specificity of the automated detection of fast bowling events was assessed against manually recorded outputs.	The relationship between the MinimaxX data and direct measures of balls bowled were assessed using the Pearson product moment correlation coefficient. MinimaxX and direct measure data were compared using independent t-tests	The bowling detection algorithm was shown to be sensitive in both training (99.0%) and competition (99.5%). Specificity was 98.1% during training and 74.0% during competition.	Low intensity bowling was not assessed.	12, 75%
Orchard et al. (2015) [47]	Australian	235	Australian professional cricketers	Fast bowling injury.	Workload patterns were assessed over a 15 year period. Injury rates were assessed for from 5 to 26 days after each workload.	95% CIs of relative risks were calculated using Taylor series expansions to assess significance at $p < 0.05$ level.	Bowlers who bowled > 50 overs in a 5 day period had increased risk when compared to those who bowled < 50overs.		14, 88%

Table 1. Continued

Study	Nationality	No. of Participants	Level of Competition	Key Dependent Variable	Methods	Statistics	Results	Limitations	Quality (score, %)
Orchard et al. (2015) [48]	Australian	235	Australian professional cricketers	Fast bowling injury	Workload patterns were assessed over a 15 year period. Injury rates were assessed for injury type and relationship to workload.	Multivariate analysis was conducted using binary logistic regression. A forward stepwise method was used, with a p value of <0.05 required for a risk factor to be included at each step.	Tendon injuries were associated with high acute workload and high previous season workload. High medium term workload was protective. For bone injury, high medium term and low career workload were risk factors. For joint injury, high previous season and career workloads were risk factors.	Diagnostic categories chosen overlapping in some injury types. Missing workload in some fast bowlers participating in non-Australian teams.	14, 88%

RPE = rate of perceived exertion. GPS = global positioning system. CK = creatine kinase. ROM = range of motion. ANOVA = one-way analysis of variance. SD = standard deviation. CI = confidence interval. ES = effect size. CV = coefficient of variation. CMJ = counter movement jump

2.4.1 Study Characteristics

A total of 984 players were investigated in the reviewed articles. Although all were elite, 10% were described as elite junior or emerging fast bowlers. While all studies recruited bowlers, key dependent variables differed markedly and included injuries (n = 7 articles) [22, 16, 39, 47, 45, 21, 48], activity profiles involving GPS and microtechnology devices (n = 6) [15, 40-42, 30, 46], strength and fitness measures (n = 3) [37, 38, 43], markers of fatigue (n = 3) [15, 43, 30], and anthropometry (n = 2) [37, 38]. Only three articles reported measures of fast bowlers' performance as key dependent variables (Table 1). Fast bowling performance was characterised by ball velocity in all three of these studies, whilst accuracy was also used as a measure of performance in two studies (Table 1). The most cited article used GPS outputs (specifically total distance and distance in speed bands) as the key dependent variables across cricket match-play [40].

2.4.2 Statistical Reporting

Magnitude-based differences via ES statistics were used in seven papers to describe both within and between subject changes. This choice of statistical reporting accounted for most (70%) of the articles not using injury as a key dependent variable. Injury focused articles used a combination of risk ratios and logistic regression to describe injury likelihood.

2.4.3 Methodological Quality

The evaluations of methodology quality scores across the articles reviewed were mostly affected by the underreporting of measures of variability in testing. Sixty-three percent clearly explained the variability of testing procedures within their study.

2.4.4 Origin of Studies Reviewed

Eighty-two percent of the articles included in the review originated from Australia, 12% were from the United Kingdom, and 6% from South Africa (Table 1).

2.4.5 Workload and Injury

From the six studies on fast bowling using injury as an outcome [22, 39, 45, 21, 47, 48], four counted the balls bowled as a measure of workload [22, 47, 48, 21]. In each of these studies, bowling workload was linked to injury likelihood. Although it appeared that 50 overs of bowling in a single week was a threshold for injury likelihood in elite fast bowlers [22], a sharp increase in acute bowling workload relative to the fast bowler's chronic workload (i.e. 4-week rolling average bowling load) also increased risk of injury [21]. Bowling workload history appeared to have a complex interaction with likelihood of injury type. Tendon injuries appeared to be associated with high acute workload and high previous season workload. High medium term workload (3-months) was identified as protective. Bone injury likelihood was increased with high medium term and low career workload. while joint injury likelihood was associated with high previous season and career workloads [48]. The remaining studies using injury as an outcome either identified a need to change the injury definition for cricket

[16], observed injury rate across a single competition period [45], or observed injury likelihood in fast bowlers with a history of spinal bone stress injury [39].

2.4.6 Workload and Performance

No articles directly linked workload and fast bowling performance. Compared with junior elite fast bowlers, elite adult fast bowlers were identified as having greater ability to functionally adapt their actions to improve bowling accuracy and tasks [44]. The age differences in these groups may imply that a high career workload has a positive influence on bowling performance.

2.4.7 Physical Requirements of Fast Bowling

In one of the three studies on the physical requirements of fast bowling, physiological measures of fatigue did not clearly identify change in physiological status during cricket training and simulated match-play [30]. Fast bowlers were also able to maintain bowling performance during these same cricket training and simulated match-play drills [15], despite markers of muscle damage increasing over bowling spells of up to 8-overs [43]. These findings suggest that elite fast bowlers were prepared for acute bowling workloads. High performing fast bowlers had greater body mass and upper-body strength than junior representative fast bowlers [37].

2.4.8 Measures of Workload

In most (80%) of the five studies using GPS and microtechnology, workload differences were identified between player roles, competition type or, competition and

training [30, 40, 42]. Fast bowlers had a greater workload than other player types, and bowling in limited over cricket generated greater sprinting per hour of play than multiday cricket [40-42, 30, 15]. Training load was often greater than the competition requirements of cricket match-play in elite players [41].

2.5 Discussion

In this systematic review, 17 studies were available to update the applied fast bowling literature since the introduction of T20 cricket. Demands of cricket match-play have been re-defined via three varying formats played at the elite level, often by the same athletes. A major component of cricket match-play is fast bowling. Fast bowling has often been associated with greater training and match-play bowling workloads [40-42, 30] and injury likelihood [45, 16, 48]. These studies have observed the relationship between accumulated bowling workloads and injury likelihood. Despite a moderate amount of available research on the mechanisms of fast bowling injury, the inconsistencies in definitions, units of time and outcomes preclude meaningful comparisons. Field-based fast bowling performance research is mostly limited to very few studies and as such, the impact of the introduction of T20 cricket is difficult to assess.

2.5.1 Workload and Injury

Measures of workload in cricket fast bowling have been modified to be very specific to the sport and position demands (i.e. counting balls bowled) [21, 47] and also via more commonly used workload monitoring methods (i.e. session rate of perceived exertion and GPS) [21, 40, 42, 30]. These workload measures are identified as internal or

external loads and are often reported as a chronic (fitness) and acute (fatigue) load [21]. Acute load (often a 7 day workload) and chronic load (often a 28 day rolling average) [21] allow investigation and management of the complex nature of fast bowling preparedness and injury likelihood.

Results from this review suggest that injury risk increases significantly for fast bowlers when acute load exceeds chronic load, particularly in the week following this “spike” in acute load [21]. When chronic loads of fast bowlers were systematically increased, injury likelihood decreased [21]. Complexity surrounds systematically increasing chronic loads in elite fast bowlers, particularly for players competing in all forms of competition. Despite restrictions on match bowling loads in 50-over (10 over restriction) and T20 (4 over restriction) cricket, appropriate preparation for upcoming multi-day competitions with greater workload requirements may be compromised.

Fast bowling generates at least some level of injury resilience [20]. However, rules restricting substitutions in match-play can expose fast bowlers to unplanned higher bowling workloads in multi-day competition. Bowlers who bowled more than 50 overs in a match had a significantly increased risk of injury in the following 21 days [22, 47]. Career workload, medium term workloads and acute workloads all need to be considered in the management of fast bowlers [48].

The most commonly reported injuries in fast bowlers include lumbar spine bone stress related-injuries. These are a concern to fast bowlers as they are difficult to predict, have

risk factors that can be unique to individuals, take considerable time to rehabilitate and can lead to other soft tissue injury [39].

The growth in T20 cricket across the world over the past 10 years has changed the commercial landscape of cricket. This commercial growth in T20 cricket has likely surpassed the output of cricket research in peer-reviewed literature. The growth of T20 cricket has resulted in recommendations for injury definition changes in cricket [16]. The range in match duration across cricket formats (4 hours to 5 days) has skewed injury rates reported relative to hours of play [16]. Reporting injury relative to days of play has normalised these injury rates [16]. Re-defining injury has also been considered as many injuries are likely to manifest during preparation phases.

Match-play and scheduling variability has provided a unique situation for cricket researchers in comparison with other team sports. T20 cricket has likely influenced the preparation strategies used by coaches, support staff and cricketers. Competition is a key contributor to the cumulative load of fast bowlers and significantly influences the preparation for upcoming competition. The lower load of one competition type might not adequately prepare the fast bowler for the higher load of upcoming competitions in other formats. Therefore, there may be a reliance on increasing training load to adequately prepare the fast bowler. Rethinking the impact of accumulative load is required, for understanding unloading or overloading, using current methodologies beyond ball counting, and across competitions of varying formats. In summary, measuring workload, injury and performance in elite fast bowlers across multi-day, 50-over and T20 competitions is complex.

2.5.2 Workload and Performance

Typically, successful team performance in cricket is measured by the number of runs scored in comparison to the opposition, and successful fast bowling in cricket is measured via how many wickets the bowlers can take for their team and the number of runs to which they can restrict the opposition [49]. However, bowling velocity and accuracy are key components of fast bowling success. Elite fast bowlers have been found to bowl only a mean $5.6 \text{ km}\cdot\text{h}^{-1}$ faster than junior participants, but importantly, perform with greater accuracy [44]. Success in fast bowling in professional teams may have other characteristics and predictors.

The length of cricket match-play often requires fast bowlers to perform over extended periods. Fast bowlers must have the physical capacity to achieve this performance requirement and the injury resilience to prevent the prevalent chronic injuries unique to fast bowling. Elite fast bowlers have greater muscle mass and strength characteristics than junior participants and other team peers [37, 38]. Typically, elite fast bowlers are physically capable of maintaining bowling performance over acute workload settings, in spite of the muscle damage and soreness associated with fast bowling [15, 43].

Cricket performance in this review was limited to training settings and cannot advance the understanding of the relationship between workload and/or physical preparation, and competition performance. A paucity exists in studies addressing cricket competition performance.

2.5.3 Physical Requirements of Fast Bowling

Elite fast bowlers demonstrated the ability to maintain bowling performance across repeated bowling spells during a training setting [15]. The influence of environmental factors on performance and fatigue over repeated bowling spells remain under-researched [15]. Investigations into the physical characteristics of fast bowlers are limited to comparisons of general strength and anthropometry assessments between senior and junior fast bowlers [37], and a descriptive study of a fast bowling cohort [38]. Findings in this review limit recommendations to coaching staff on the physical requirements of elite fast bowling.

2.5.4 Measures of Workload

Typically, GPS devices have been used in cricket to identify the different activity profiles across competition types. Shorter formats of cricket match-play have been associated with greater playing intensity [42]. Compared with other types of bowlers and field positions, fast bowlers not only experienced greater match-play demands [41, 40, 30], but also had greater activity profiles during physical preparation [30]. Greater match and physical preparation workloads in fast bowlers differentially influenced the neuromuscular, endocrine and perceptual fatigue responses compared with non-fast bowlers [30]. Fast bowlers had greater cortisol and lower testosterone concentrations than non-fast bowlers, while perceived wellbeing was also greater in fast bowlers than non-fast bowlers. Differences in neuromuscular function (measured via a countermovement jump) remained unclear [30]. Nonetheless, it is likely that fast

bowlers were generally well-prepared for the workload requirements of fast bowling and cricket match-play.

Along with the GPS technology, the microtechnology (i.e. tri-axial accelerometer and gyroscope) housed within the GPS unit has successfully been integrated to automate the monitoring of bowling workloads [46]. Automated bowling workload monitoring will likely increase accuracy of fast bowling workload measures. It is postulated that variability in bowling intensity arises from various training and competition workloads. Including all balls bowled in this workload definition may not provide an accurate measure of the intensity of the workload [50]. In conjunction with the current workload methodology of counting balls bowled, microtechnology may provide an opportunity to gain insight into bowling intensity via accelerometers and gyroscopes housed within wearable tracking devices. The relatively large number of citations recorded in articles using GPS or wearable technology in cricket may further highlight the direction and pace of cricket workload monitoring trends.

2.5.6 Limitations

Limitations in the current fast bowling literature remain. It is likely that the current longitudinal research has been influenced significantly by ever changing schedules in both domestic and international cricket. In this systematic review, 82% of the articles reviewed originated from Australia; applying these results to fast bowlers from other cricketing nations may require a degree of caution. Consideration should also be given to the potential influence of changing environmental factors, field sizes, and ground/pitch conditions that may change across the world. Also, within the limitation

of high performance cricket, it is possible that workload monitoring in aspiring cricketers may require additional research, given the increasing opportunities for year-long cricket, even at the domestic level.

2.6 Conclusions and Implications

The physical preparation of elite cricketers has become more complex since 2005 when T20 cricket was introduced into both international and domestic schedules. T20 cricket is recognised as having greater intensity and reduced overall workload than multi-day cricket. Although it appears that elite fast bowlers may be prepared for the acute workload demands of fast bowling, injury likelihood increases when those acute workloads exceed the chronic workload history of the fast bowler. Workload in fast bowlers has typically been measured as balls bowled. Advances in GPS and microtechnology have allowed some insight into the workload variance of preparation and cricket match-play across formats. Despite the relatively significant evolution in match-play since 2005, there have been few descriptions in peer reviewed literature of relationships among elite fast bowling workload, injury and performance. Bowling performance has also been mostly limited to ball accuracy and velocity. Introducing novel and practical measures of performance aside from ball velocity and accuracy requires further exploration. Future research should aim to include the quality and intensity of fast bowling performance as a major dependent variable, improve the workload monitoring strategies utilised in elite fast bowlers, and advance the understanding of varying match-play demands on injury likelihood.

2.7 Compliance with Ethical Standards

2.7.1 Funding

No sources of funding were used to assist in the preparation of this article.

2.7.2 Conflicts of Interest

Dean McNamara, Tim Gabbett and Geraldine Naughton declare that they have no conflicts of interest relevant to the content of this review.

**Chapter 3: Physical preparation and competition workloads and fatigue
responses of elite junior cricket players**

This study has been accepted for publication following peer review. Full reference details are:

McNamara DJ, Gabbett TJ, Naughton G, Farhart P, and Chapman P. Physical preparation and competition workloads and fatigue responses of elite junior cricket players. *International Journal Sports Physiology Performance*, 2013, 8 (5), 517-526.

3.1 Abstract

We investigated key fatigue and workload variables of cricket fast bowlers and non-fast bowlers during a 7-week physical preparation and 10-day intensified competition period. Twenty-six elite junior cricketers (mean \pm SD age, 17.7 ± 1.1 yr) were classified as fast bowlers (n=9) or non-fast bowlers (n=17). Individual workloads were measured via GPS technology and neuromuscular function (countermovement jump [relative power and flight time]), endocrine (salivary testosterone and cortisol concentrations) and perceptual well-being (soreness, mood, stress, sleep quality, and fatigue) markers were recorded. Fast bowlers performed greater competition total distance [median (interquartile range) 7049 (3962) m vs 5062 (3694) m], including greater distances at low and high speeds, more accelerations [40 (32) vs 19 (21)], and higher Player Load™ [912 (481) arbitrary units vs 697 (424) arbitrary units] than non-fast bowlers. (Mean \pm 90% CI, % likelihood) cortisol concentrations were higher in the physical preparation ($d = -0.88 \pm 0.39$, 100%) and competition phases ($d = -0.39 \pm 0.30$, 85%), and testosterone concentrations lower ($d = 0.56 \pm 0.29$, 98%) in the competition phase in fast bowlers. Perceptual well-being was poorer in non-fast bowlers during competition only ($d = 0.36 \pm 0.22$, 88%). Differences in neuromuscular function between groups were unclear during physical preparation and competition. These findings demonstrate differences in the physical demands of cricket fast bowlers and non-fast bowlers, and suggest that these external workloads impact differentially on the neuromuscular, endocrine and perceptual fatigue responses of these players.

3.2 Introduction

Cricket is a popular team sport, played predominantly in Commonwealth countries. Comprising two teams of 11 players, specific positional roles can be classified into various sub-categories including batsmen, bowlers (sub-categories fast, medium, spin) and fielders (sub-categories wicket-keepers, inner and outer). Finer classifications within these sub-categories can also be identified. Whilst each player has specific roles within a team, all players are required to field throughout the course of a game. Variations in game formats exist including multi-day, 50-over and 20-over cricket. Differences between formats are identified in the length of each match with multi-day cricket lasting up to 5 consecutive days, and 50-over and 20-over matches completed in approximately 8 and 4 hours, respectively.

Time motion analysis has been used to describe the physical demands of cricket batting and fielding [51]. Global positioning system technology has contributed to an understanding of the differences in match load and intensities between 1-day and multi-day cricket formats. Peterson and colleagues identified differences in match intensity between fast bowlers and non-fast bowlers; fast bowlers covered more distance and at greater intensities than non-fast bowlers [40]. In the same study it was identified that game format also influenced the load and intensity on fast bowlers and non-fast bowlers, with 20-over matches resulting in higher average intensities than 50-over and multi-day cricket. Previous research has identified that while 1-day cricket formats had greater intensities, multi-day cricket involved greater overall load [42]. The activity profiles of competitive match-play and cricket training activities typically used to develop skill and physical fitness have also been investigated [41]. Peterson and colleagues found higher heart rate and blood lactate concentration during conditioning

training than competition [41]. Few other studies have investigated the physical demands of cricket, with the majority of these studies limited to the acute responses to cricket-related tasks reporting heart rate, blood lactate concentration and hydration status in bowling spells [52, 53]. Duffield and colleagues investigated both physiological and performance responses to repeated spells of fast bowling; 6-over spells of fast bowling resulted in increases in rating of perceived exertion (peaking at 6.5 ± 0.8 arbitrary units), blood lactate concentration (from 1.5 ± 0.3 to 5.0 ± 1.5 mmol.L⁻¹), and reductions in blood glucose concentrations (from 6.3 ± 0.7 to 5.4 ± 0.4 mmol.L⁻¹) [15]. Collectively, these findings highlight the intense physical demands of cricket fast bowling.

Several studies have monitored the fatigue response of team and individual sport athletes using a wide range of testing protocols including countermovement jumps (CMJ), salivary endocrine markers (e.g. testosterone and cortisol concentrations) and perceptual well-being questionnaires [54, 55]. Although no single marker has established sensitivity to detect overall fatigue in sporting populations [13], these measures offer a useful method of monitoring the physical and emotional responses of athletes to a given workload [56]. However, while the physical demands of cricket match-play have previously been described, and differences in match load and intensities exist between fast bowlers and non-fast bowlers, no study has monitored markers of fatigue during preparation and competition periods in the same cricketers. The paucity of research detailing the demands of fast bowling is surprising, particularly given reports of higher injury rates than other playing positions [22, 57]. Furthermore, given that the majority of fast bowling injuries have been attributed to “overuse” mechanisms [17], an understanding of the physical preparation and match loads of fast

bowlers, and fatigue associated with these activities would appear critical to ensure the health and fitness of these athletes [17].

To date, no study has investigated the physical preparation and match-play workloads of cricketers, and described the endocrine, neuromuscular, and perceptual fatigue associated with playing this sport. Furthermore, the relative physiological stress imposed on fast bowlers and non-fast bowlers has yet to be identified. With this in mind, the purpose of this study was to profile and identify key fatigue and workload variables of cricket fast bowlers and non-fast bowlers during a 7-week physical preparation period and an intensified 10-day competition period.

3.3 Methods

3.3.1 Subjects

Twenty-six male cricketers (mean \pm SD age, 17.7 ± 1.1 yr) selected in the New South Wales National Cricket Championship squads participated in this study. All participants were highly motivated players from two separate aged group squads (Under 17 and Under 19). All players were competing for their individual clubs and training with the elite age group squads, and were injury free at the start of the study. All participants received a clear explanation of the study, and written consent was obtained. The Australian Catholic University Human Research Ethics Committee approved all experimental procedures.

3.3.2 Research Design

This study described the workloads and markers of neuromuscular, endocrine and

perceptual fatigue of male cricketers in response to a 7-week physical preparation period and 10-day intensified period of competition. Physical preparation consisted of one structured session per week and at least one other club/school training session and match per week. Each training session was defined from the beginning to the completion of any prescribed physical activity or exercise by the coach. These sessions had consistent start and completion times. The competition schedule was made up of three 50-over matches, two 2-day matches, and two 20-over matches. This schedule allowed for rest on days 4 and 7 of the tournament.

3.3.3 Workload Measures

Movement was recorded by a GPS unit (minimax S4, Catapult Innovations, Melbourne, Australia) sampling at 10 Hz. Players wore the GPS unit in a small vest, on the upper back during both physical preparation and competition. The 10 Hz GPS units have acceptable reliability for speed, distance, position, and acceleration data [58]. Additional data were collected from the unit's tri-axial accelerometer, sampling at 100 Hz to calculate Player Load™ [24]. One hundred and seventy match files and 83 physical preparation files were collected over the 7-week preparation and 10-day competition periods. Participants were assigned to one of two different groups; fast bowlers (n=9) and all other players (non-fast bowlers) (n=17). Players were defined and allocated to the 2 positional groups by coaching staff.

The following movement categories were used: (a) low-speed activity 0-5 m/s; (b) high-speed running ≥ 5.1 m.s⁻¹; and (c) sprinting ≥ 7.1 m.s⁻¹ [59]. Data were also classified into moderate (1.12-2.78 m.s⁻²), and maximal (≥ 2.79 m.s⁻²) acceleration bands [59]. Logan Plus 4.7.1 software (Catapult Innovations, Melbourne, Australia) was used to

process all GPS and accelerometer data. Player Load™ was calculated in Logan Plus using accelerometer data as previously described [24, 60].

3.3.4 Fatigue Markers

A reduction in neuromuscular, hormonal and/or biological status will indicate that athletic performance may be compromised.

3.3.4.1 Performance Measures

Baseline CMJ data were collected prior to commencement of the training session or match. A standardized warm up was performed prior to completion of the CMJ. This warm up included dynamic stretches and a series of running patterns that progressively increased in intensity. A single CMJ was collected after this warm up and standardized practice jumps. Following adequate recovery, each participant completed a series of 5 continuous CMJs. All CMJs were completed with athletes keeping their hands on their hips. No instruction was given on the depth of the jump [54].

All jumps were performed on a Kistler Quattro Force Plate (Kistler, Winterthur, Switzerland), and collected using Quattro Jump software (Kistler, Winterthur, Switzerland). Once collected, data were exported into a customized Microsoft Excel Spreadsheet (Microsoft, Redmond, USA) for further analysis of relative peak power and flight time. Coefficients of variation (CV) as a percentage of the relative peak power and flight time were 3.4% and 5.7%, respectively.

3.3.4.2 Perceptual Fatigue Measures

Subjective perceptions of well-being were reported for each training session and

throughout each day of competition. Subjective perceptions of well-being were assessed using a 5 point scale for fatigue, sleep quality, general muscle soreness, stress levels and mood with lower scores indicating a poorer state of well-being [61]. The CV as a percentage of the perception of well-being was 4.2%.

3.3.4.3 Endocrine Measures

Salivary analysis was used to measure testosterone and cortisol responses to physical preparation and competition demands. Saliva samples were collected using a 10 mm x 30 mm salivary oral swab (Salimetrics, PA, USA). Saliva samples were collected at 8 am on Thursday mornings during the physical preparation phase and every day during competition. Participants were instructed to place the oral swab underneath their tongue for one minute and then place the swab in the storage cryovial. Participants refrained from eating for 60 minutes prior to collection. All saliva samples were stored at -20° C until subsequent analysis. Cortisol and testosterone were determined in duplicate by enzyme-linked immunosorbent assay (Salimetrics, PA, USA) using a microplate reader (XMark, BioRad, CA, USA). Coefficients of variation as a percentage of the testosterone and cortisol assays were 9.2% and 3.0%, respectively.

3.3.5 Statistical Analysis

To eliminate the variation of individual patterns and fluctuations of CMJ measures, all CMJ data were converted to a Z-score calculated for each individual player before analysis. Z-scores were calculated with the following formula: (individual cricketers score—individual cricketers average) divided by individual cricketer's standard deviation. Data were tested for normality using a Shapiro-Wilk test. As GPS data were not normally distributed, Cliff's Delta (*Cd*) and 90% CI were used as a measure of ES.

Median and interquartile ranges were reported for all non-normally distributed data [61, 62]. Cliff's Delta scores were defined as 0.15 = small, 0.33 = moderate, and 0.47 = large [64].

Salivary testosterone and cortisol concentrations, CMJ, and perceptual well-being data were log transformed to reduce bias as a result of non-uniformity of error. Cohen's effect size statistic (d) with 90% CI was used to compare the magnitude of difference between fast bowlers and non-fast bowlers. Cohen's effect sizes of 0.2, 0.5 and >0.8 were considered small, moderate and large, respectively [65]. Magnitudes of differences between the two groups were classified as substantially greater or lesser when there was a $\geq 75\%$ likelihood of the effect being equal to or greater than the smallest worthwhile change (SWC) estimated as $0.2 \times$ between-subject standard deviation (small ES). Effects with less certainty were classified as trivial and where the $\pm 90\%$ CI of the ES crossed the boundaries of ES -0.2 and 0.2 , the effect was reported as unclear [66].

3.4 Results

The median distance covered by fast bowlers was greater than non-fast bowlers in both the physical preparation ($Cd=0.34 \pm 0.2$, 94%) and competition ($Cd=0.36 \pm 0.18$, 97%) settings (Table 2). The greater distance covered by fast bowlers was achieved through greater distances at both low and high speeds. The fast bowlers' frequency of maximal accelerations were greater than non-fast bowlers for both physical preparation ($Cd=0.43 \pm 0.21$, 99%) and competition ($Cd=0.55 \pm 0.27$, 99%). Player Load™ was greater in fast bowlers in competition ($Cd=0.32 \pm 0.16$, 96%) but unclear in the physical preparation period ($Cd=0.16 \pm 0.2$, 53%).

Table 2. Activity profiles during physical preparation and competition in fast bowlers and non-fast bowlers.

Variable		Physical Preparation	<i>Cd</i> ± 90%CI, %Likelihood	Competition	<i>Cd</i> ± 90%CI, %Likelihood
Distance (m)	Fast Bowlers	5372 (3635)	0.34 ± 0.2, 94%	7049 (3962)	0.36 ± 0.18, 97%
	Non-Fast	3509 (2797)		5062 (3694)	
Low Speed Distance (m)	Fast Bowlers	5603 (3322)	0.31 ± 0.2, 91%	6546 (3433)	0.30 ± 0.16, 94%
	Non-Fast	3395 (2673)		4915 (3441)	
High Speed Distance (m)	Fast Bowlers	280 (300)	0.54 ± 0.26, 91%	472 (492)	0.90 ± 0.44, 100%
	Non-Fast	32 (112)		60 (88)	
Fast Efforts (#)	Fast Bowlers	24 (26)	0.62 ± 0.3, 99%	31 (28)	0.89 ± 0.44, 100%
	Non-Fast	3 (9)		4 (7)	
Player Load TM (au)	Fast Bowlers	703 (450)	0.16 ± 0.2, 53%	912 (481)	0.32 ± 0.16, 96%
	Non-Fast	598 (427)		697 (424)	
Acc 1.12-2.78m.s ⁻² (#)	Fast Bowlers	35 (30)	0.43 ± 0.21, 99%	40 (32)	0.55 ± 0.27, 99%
	Non-Fast	18 (21)		19 (21)	
Acc >2.78 m.s ⁻² (#)	Fast Bowlers	1 (2)	0.05 ± 0.19, 76%	1 (3)	0.04 ± 0.18, 81%
	Non-Fast	1 (3)		1 (3)	
Relative Distance (m/min)	Fast Bowlers	49 (23)	0.33 ± 0.2, 91%	70 (16)	0.62 ± 0.31, 99%
	Non-Fast	39 (26)		57 (22)	
Low Speed (m/min)	Fast Bowlers	46 (19)	0.31 ± 0.2, 91%	64 (16)	0.52 ± 0.26, 99%
	Non-Fast	38 (25)		50 (21)	
High Speed (m/min)	Fast Bowlers	2 (3)	0.53 ± 0.26, 99%	5(3)	0.91 ± 0.45, 100%
	Non-Fast	0.3 (1.4)		0.6 (0.9)	
Fast Efforts (#/min)	Fast Bowlers	0.2 (0.2)	0.63 ± 0.31, 99%	0.3 (0.2)	0.90 ± 0.44, 100%
	Non-Fast	0.02 (0.1)		0.04 (0)	
Player Load TM (au/min)	Fast Bowlers	7 (3)	0.21 ± 0.2, 69% trivial	9 (3)	0.49 ± 0.24, 99%
	Non-Fast	6 (3)		6 (3)	
Acc 1.12-2.78 m.s ⁻² (#/min)	Fast Bowlers	0.4 (0.2)	0.50 ± 0.24, 99%	0.4 (0.2)	0.59 ± 0.29, 99%
	Non-Fast	0.2 (0.2)		0.2 (0.1)	
Acc >2.78 m.s ⁻² (#/min)	Fast Bowlers	0.01 (0)	0.04 ± 0.17, 84%	0.01 (0)	0.04 ± 0.17, 82%
	Non-Fast	0.01 (0)		0.01 (0)	

Data are median (interquartile range). Acc = acceleration. Cliff's Delta (*Cd*) scores were defined as 0.15 = small, 0.33 = moderate, and 0.47 = large. Differences between the two groups were classified as substantially greater or lesser when there was a ≥75% likelihood of the effect being equal to or greater than the smallest worthwhile change estimated as 0.2 x between-subject standard deviation.

The CMJ relative power (CMJRelP) and flight time (CMJFTime) over the physical preparation and competition phases are shown in Figures 5 and 6, respectively. Differences in CMJRelP between the fast bowling and non-fast bowling groups were unclear in both the physical preparation ($d = -0.16 \pm 0.38$, 51%) and competition phases ($d = 0.19 \pm 0.24$, 53%). Differences in CMJFTime between the fast bowling and non-fast bowling groups were also shown to be unclear in the physical preparation ($d = 0.34 \pm 0.47$, 69%) and competition phases ($d = 0.02 \pm 0.23$, 84%).

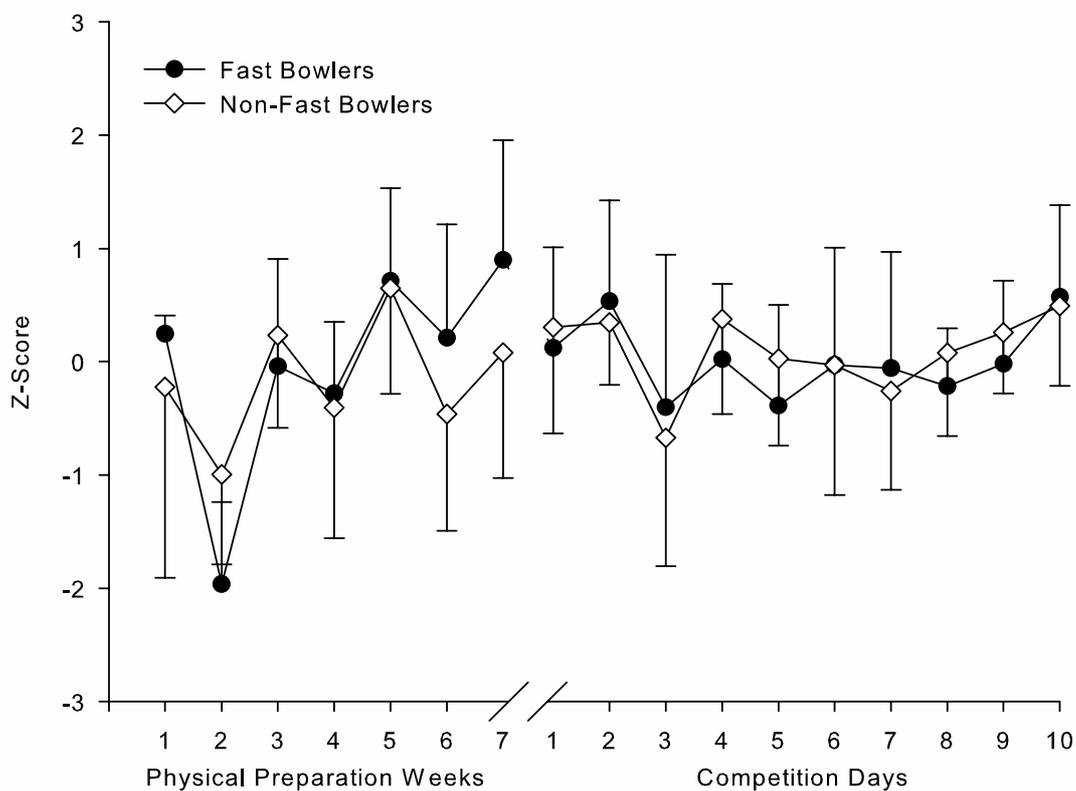


Figure 5. Counter movement jump relative power for fast bowlers and non-fast bowlers during training and competition.

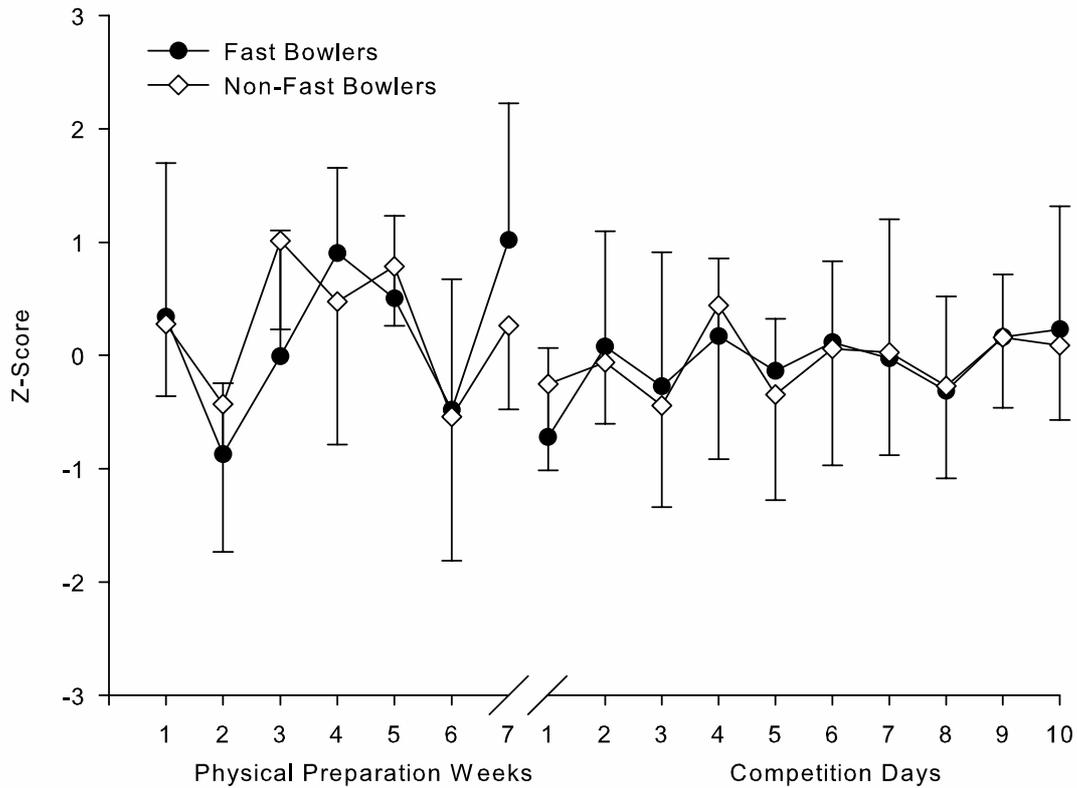


Figure 6. Counter movement jump flight time for fast bowlers and non-fast bowlers during training and competition.

Over the physical preparation period, the fast bowling group recorded almost certainly greater cortisol concentrations ($d = -0.88 \pm 0.39$, 100%) than the non-fast bowling group. Figure 7 shows that this trend was consistent over the entire 7 weeks. Cortisol concentrations were also likely greater in the fast bowling group during the competition phase ($d = -0.39 \pm 0.30$, 85%) (Table 3). The fast bowling group recorded greater mean cortisol concentrations for over 70% of the competition phase; the non-fast bowling group recorded greater mean concentrations in the final three days of competition only.

Table 3. Differences in neuromuscular, endocrine and perceptual well-being between fast bowlers and non-fast bowlers during the physical preparation and competition phases.

Test	Fast Bowlers vs. Non-Fast Bowlers	
	Physical Preparation ($d \pm 90\%CI$, % Likelihood)	Competition ($d \pm 90\%CI$, % Likelihood)
CMJRelP	-0.16 \pm 0.38, 51% trivial Unclear	0.19 \pm 0.24, 53% trivial Unclear
CMJFTime	0.34 \pm 0.47, 69% Unclear	0.02 \pm 0.23, 84% trivial Unclear
Cortisol Concentration	-0.88 \pm 0.39, 100% Almost certainly negative (FB>Non)	-0.39 \pm 0.30, 85% Likely negative (FB>Non)
Testosterone Concentration	0.22 \pm 0.33, 55% Unclear	0.56 \pm 0.29, 98% Very likely positive (Non>FB)
Perceptual Well-being	0.31 \pm 0.39, 68% Unclear	-0.36 \pm 0.22, 88% Likely negative (FB>Non)

Data are reported as Cohen's effect size (d) \pm 90% confidence intervals (CI) and qualitative descriptors. FB = Fast Bowling group; Non = Non-Fast Bowling group. CMJRelP = Countermovement jump relative power; CMJFTime = Countermovement jump flight time. Differences between the two groups were classified as substantially greater or lesser when there was a $\geq 75\%$ likelihood of the effect being equal to or greater than the smallest worthwhile change estimated as 0.2 x between-subject standard deviation. Cohen's d was defined as 0.2 = small, 0.5 = moderate and >0.8 = large.

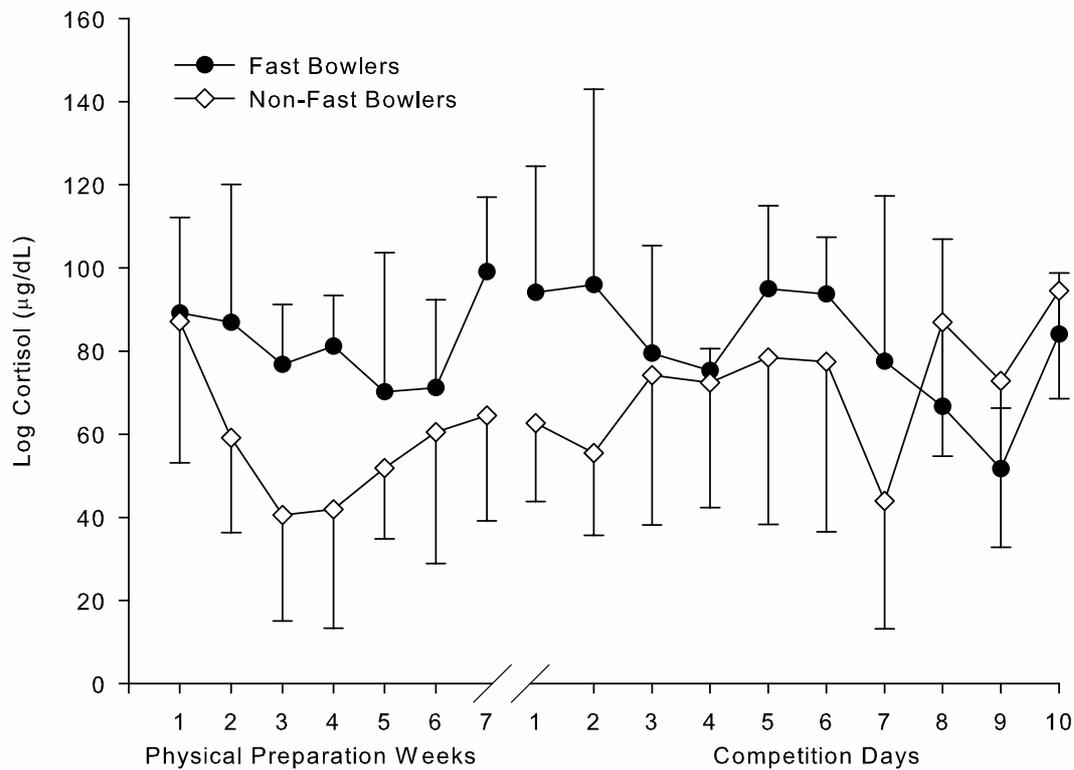


Figure 7. Cortisol concentrations for fast bowlers and non-fast bowlers during training and competition. All scores are transformed using the log function.

During the competition phase, testosterone concentrations were very likely greater in the non-fast bowling group ($d = 0.56 \pm 0.29$, 98%) than the fast bowling group. Differences in testosterone concentrations between the fast bowling and non-fast bowling groups were unclear in the physical preparation phase ($d = 0.22 \pm 0.33$, 55%) (Figure 8).

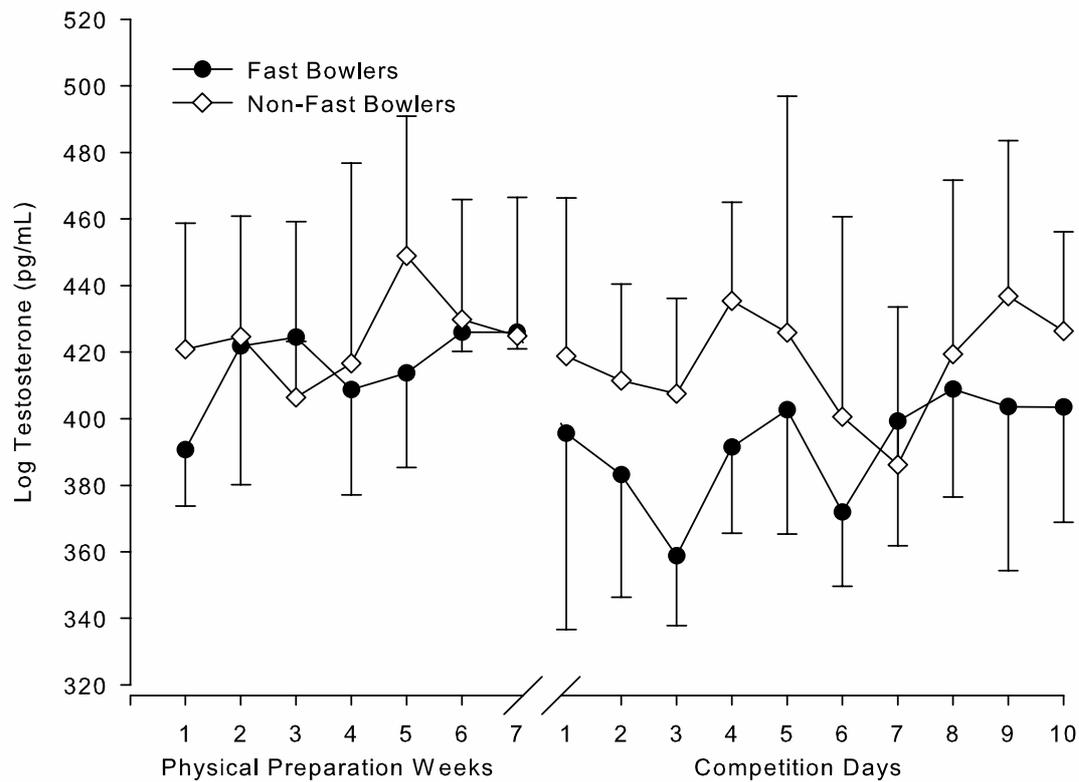


Figure 8. Testosterone concentrations for fast bowlers and non-fast bowlers during training and competition. All scores are transformed using the log function.

Well-being scores were shown to be likely greater in the fast bowling group during the competition phase ($d = -0.36 \pm 0.22, 88\%$). Differences in well-being scores between the fast bowling and non-fast bowling groups were unclear in the physical preparation phase ($d = 0.31 \pm 0.39, 68\%$) (Figure 9).

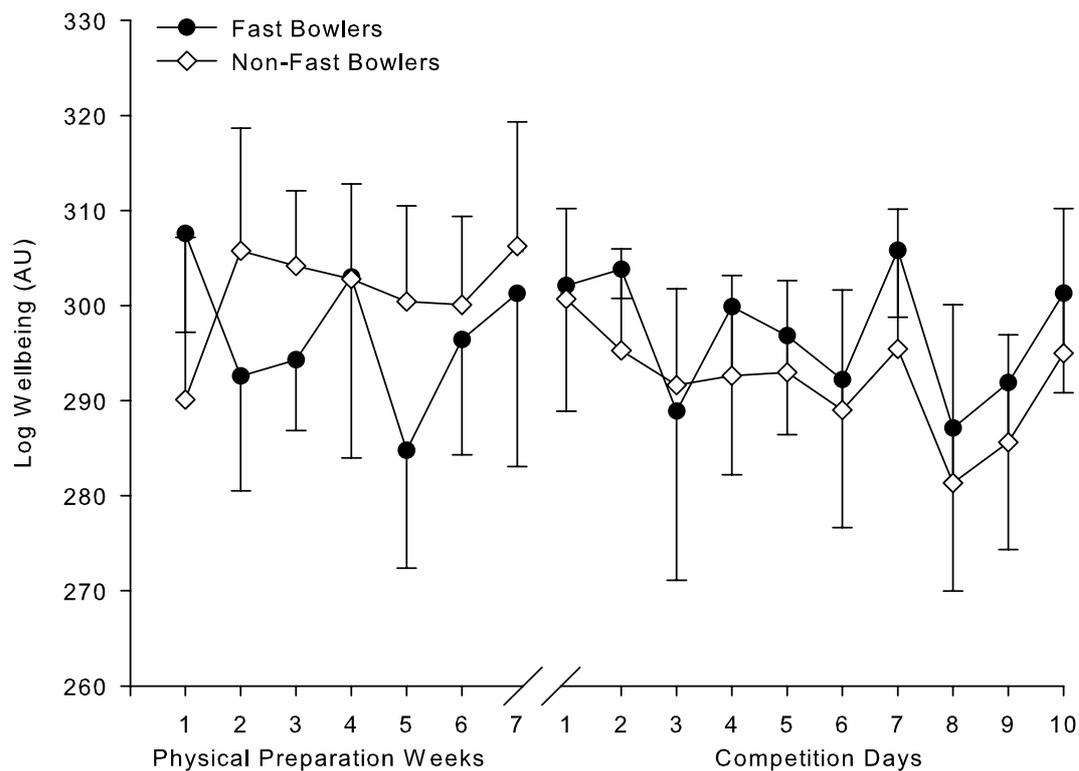


Figure 9. Perceptual well-being scores for fast bowlers and non-fast bowlers during training and competition. All scores are transformed using the log function.

3.5 Discussion

This study investigated key workload and fatigue differences between fast bowlers and non-fast bowlers during a 7-week physical preparation period and 10-day period of intensified competition. The results demonstrated that fast bowlers consistently performed at greater intensities and performed more high speed running than non-fast bowlers. Furthermore, fast bowlers exhibited greater physical preparation and competition cortisol concentrations, lower competition testosterone concentrations, less perceptual fatigue during competition, and similar CMJ performances to non-fast bowlers. Overall, these findings demonstrate differences in the physical demands of cricket fast bowlers and non-fast bowlers, and that these external

workloads impact differentially on the neuromuscular, endocrine and perceptual fatigue responses of these players.

Fast bowlers completed greater external workloads (reflected by greater amounts of low speed activity, high speed running, and higher Player Load™ scores) during competition and physical preparation than non-fast bowlers. These findings support previous studies identifying the physical demands of cricketers [40]. The higher physical preparation workloads in the fast bowling group are likely to reflect the preparation required to successfully participate in competition. Given that fast bowlers are required to participate in batting and fielding training drills, it is likely that the difference in physical preparation workloads between groups can be attributed to the act of fast bowling itself. Identifying whether the fast bowling task is the sole explanation for variations in competition workloads is more complicated, as individual fielding positional requirements, the random nature of player's involvement in a match event, and variations in the length of time before a batsman is dismissed may all influence the external work performed by fast bowlers.

We found higher cortisol concentrations across the physical preparation and competition periods in fast bowlers than non-fast bowlers. The higher cortisol concentrations are possibly linked to the higher workloads and intensities of these players relative to non-fast bowlers. Alex-Sy *et al* [67] reported elevated cortisol concentrations during a pre competition period in soccer players, and showed that the endocrine responses coincided with increases in emotional stress. The poorer perceptions of well-being during competition, coupled with the higher cortisol concentrations in the non-fast bowlers in the final 3 days of the competition period, may reflect the greater psychological stress associated with batting in cricket [68].

The results of this study also showed lower testosterone concentrations in fast bowlers during the competition period. Previous studies of adolescent rugby players have identified testosterone concentrations as a better measure of tiredness (as estimated from a self-reported questionnaire) than cortisol concentrations [55]. While our results are in general agreement with those of Maso *et al* [55], there may be differences in the training activities of rugby players and cricketers that require consideration when interpreting individual testosterone responses as a measure of tiredness. It is likely that rugby players participate in a greater volume of resistance training sessions, and are also exposed to significantly greater contact demands than cricketers, which may influence the acute testosterone concentration responses [69].

Previous studies have shown neuromuscular function changes over the course of a competition week and playing season in Australian football and rugby league players [54, 61]. In the present study, there was no clear evidence that neuromuscular function deteriorated during the physical preparation or competition periods. It is possible that the total training load prescribed during the physical preparation period in the cricket players of the present study was insufficient to reduce neuromuscular function in these athletes. Indeed, in comparison with Australian football, fast bowlers have been shown to complete less than half the total metres per minute during competition [60], and exhibit significantly lower training intensities than other team sports [70]. Furthermore, this study only assessed lower body neuromuscular function. It is possible that an upper body neuromuscular function test might provide greater sensitivity for detecting neuromuscular fatigue, particularly in the fast bowling group.

A major new finding of this study was the uncoupling of neuromuscular, endocrine and perceptual fatigue markers in response to external load, particularly during the competition period. Although results from competition cortisol and testosterone concentrations suggested

that fast bowlers were in a greater catabolic state than non-fast bowlers, neuromuscular function was maintained at levels comparable to non-fast bowlers. Furthermore, fast bowlers reported less perceptual fatigue than non-fast bowlers. While the endocrine, neuromuscular and perceptual measures used in this study have been routinely used as markers of fatigue, previous investigators have commonly reported that no single marker has adequate sensitivity to detect the fatigue associated with intense sporting activities [56]. It is also possible that the sensitivity of some markers could be sport-specific. That is, the markers used to identify fatigue in some high-intensity (e.g. soccer) [67] or collision (e.g. Australian football, rugby league) [54, 61] sports may differ from the markers used to identify fatigue in cricket. Equally, fast bowlers may be better physically and psychologically prepared to tolerate higher competition loads. Indeed, fast bowlers performed higher external loads in both physical preparation and competition. It is likely that these external loads during training led to greater resilience during the competition period as reflected in the greater perceptions of well-being and maintenance of neuromuscular function during competition.

While this study has described important workload and fatigue variables associated with cricket physical preparation and competition, several limitations warrant discussion. Firstly, our sample size was relatively small, and consequently our statistical power is likely to be low. We reconciled this limitation with the knowledge that the players included in this study were the best junior (Under 17 and 19) cricketers in the state, and were preparing for, and competing in the highest level of competition in the country. Secondly, while the training demands during the physical preparation period were documented, it was not possible to control or monitor any additional activities that players performed outside of these structured physical preparation sessions and matches. Finally, while these results have direct applications to elite junior cricket players, it is likely that the physical demands and fatigue associated with senior international

cricket differs significantly from the present results. As such, these results are unlikely to be generalizable to elite first-class cricketers.

3.6 Conclusions

In conclusion, we investigated the external workloads and fatigue responses of fast bowlers and non-fast bowlers during a 7-week physical preparation period and 10-day period of intensified competition. The results of this study demonstrate that fast bowlers perform at greater intensities and perform more high speed running than non-fast bowlers. Fast bowlers exhibit greater physical preparation and competition cortisol concentrations, lower competition testosterone concentrations, less perceptual fatigue during competition, and similar CMJ performances to non-fast bowlers. These findings demonstrate differences in the physical demands of cricket fast bowlers and non-fast bowlers, and that these external workloads impact differentially on the neuromuscular, endocrine and perceptual fatigue responses of these players.

3.7 Practical Applications

Questionnaire based well-being measures are a cost effective and simple tool to monitor fatigue in athletes [13]. Interpretations of questionnaire based well-being data should be considered closely in cricketers. For example, variations in performances and emotional stresses in non-fast bowlers during competition periods may influence perceptions of fatigue to a greater degree than the physical load associated with the competition itself.

Monitoring neuromuscular function, via CMJs has been shown to be a useful marker of fatigue in team based sports [70]. In this study, CMJs were limited in identifying changes in neuromuscular function. These results suggest that the prescribed training loads were either

insufficient to elicit neuromuscular fatigue, or that players were physically and psychology prepared to tolerate the loads prescribed during the physical preparation and competition periods. A combination of neuromuscular, endocrine, and perceptual markers may facilitate the identification of fatigue during cricket training and competition.

3.8 Acknowledgments

We would like to thank the players and coaches, particularly Michael Maclennan, of the New South Wales Cricket male National Cricket Championship squads. Special thanks is also extended to Michael Pappas who participated as a research assistant throughout this project.

Chapter 4: The validity of microsensors to automatically detect bowling events and counts in cricket fast bowlers

This study has been accepted for publication following peer review. Full reference details are:

McNamara DJ, Gabbett TJ, Chapman P, Naughton G, Farhart P. The validity of microsensors to automatically detect bowling events and counts in cricket fast bowlers. *International Journal of Sports Physiology And Performance*. 2015;10(1):71-5.

4.1 Abstract

Bowling workload is linked to injury risk in cricket fast bowlers. This study investigated the validity of microtechnology in the automated detection of bowling counts and events, including run up distance and velocity in cricket fast bowlers. Twelve highly skilled fast bowlers (mean \pm SD age; 23.5 ± 3.7 yr) performed a series of bowling, throwing, and fielding activities in an outdoor environment during training and competition, while wearing a microtechnology unit (MinimaxX). Sensitivity and specificity of a bowling detection algorithm was determined by comparing the outputs from the device with manually recorded bowling counts. Run up distance and run up velocity were measured and compared with microtechnology outputs. No significant differences were observed between direct measures of bowling and non-bowling events and true positive and true negative events recorded by the MinimaxX unit ($P=0.34$, $r = 0.99$). The bowling detection algorithm was shown to be sensitive in both training (99.0%) and competition (99.5%). Specificity was 98.1% during training and 74.0% during competition. Run up distance was accurately recorded by the unit with a percentage bias of 0.8% ($r = 0.90$). The final 10 m (-8.9%, $r = 0.88$) and 5 m (-7.3%, $r = 0.90$) run up velocities were less accurate. The bowling detection algorithm from the MinimaxX device is sensitive to detect bowling counts in both cricket training and competition. Although specificity is high during training, the number of false positive events increased during competition. Additional bowling workload measures require further development.

4.2 Introduction

Cricket is a popular team sport, played predominantly in Commonwealth countries. Comprising two teams of 11 players, specific roles of players can be classified into various sub-groups including batsmen, fast bowlers, spin bowlers and wicket keepers. Fast bowlers usually account for three to five of the 11 players within each team. Competition bowling workloads depend on both match type and the match play strategy adopted by the team captain, whilst training workloads reflect the volume, intensity, and frequency prescribed by team coaches and support staff.

Fast bowlers have greater physical workloads and higher injury rates than other player types [22, 40]. To date, fast bowling workload monitoring has been limited to the number of balls bowled. When self-reported accurately, this is a cost effective and practical method of monitoring bowling workload for large groups of athletes. However, there is the potential for inaccuracies in athlete self-reporting, particularly during training. In elite cricket, where fast bowling workloads have been attributed to injury likelihood, accurate measures of workload are vital in the management of fast bowlers.

With the assumption that not every ball bowled during training is representative of competition intensity, the simple method of reporting all balls bowled becomes a relatively broad definition of bowling workload. Ball speed is attributed to various parts of the bowling action including the run up speed [71]. Modification of bowling action may influence the delivery speed and bowling performance, as well as the total load experienced by the bowler during that event. Bowling workload monitoring has also been identified as vital in both injury prevention and physical conditioning [22]. Given the demanding nature of fast bowling, and the high risk of

injury, efficient and accurate measures of bowling events are vital in understanding the workloads of fast bowlers and the fatigue associated with this activity.

Global positioning system technology has been shown to provide a valid measure of acceleration, velocity and total distance [58, 72]. This technology has contributed to an understanding of the differences in match load and intensities between one-day and multi-day cricket formats [42, 41]. With the addition of accelerometer and gyroscope technologies, these microtechnology units have become a powerful tool in monitoring athlete workloads. Indeed, manufacturers of microtechnology units have designed specific algorithms that have been used in other team sports to automatically identify important match and training events [41]. Researchers in collision sports have previously validated the automated quantification of tackles using microtechnology units [18, 25]. However, the accuracy of this system in fast bowling is yet to be validated. The significance of such a tool for fast bowling workload monitoring is twofold. First, it may improve the accuracy and ease in identification of important competition events, and second, it may allow for greater accuracy and easier interpretation of segmented and total bowling workloads during training.

With this in mind, the primary aim of this study was to validate the use of microtechnology devices in the automated detection of bowling events and counts in cricket fast bowlers during training and competition against current monitoring methods. A secondary aim of this study was to further refine the monitoring of bowling intensities, more specifically, run up velocity and distance. This will advance the methods and accuracy of elite fast bowling workload monitoring during training and competition.

4.3 Methods

4.3.1 Subjects

Twelve highly skilled fast bowlers (mean \pm SD age; 23.5 \pm 3.7 yr) participated in this study. Participants were competing professionally (International, $n = 2$; First class, $n = 8$), or in a first grade competition ($n = 2$) at the time of the study. Both right handed ($n = 9$) and left-handed ($n = 3$) bowlers participated in this study. All participants were free from injury or any other medical condition that would compromise participation. All participants received a clear explanation of the study, and written consent was obtained. The Australian Catholic University Human Research Ethics Committee approved all experimental procedures.

4.3.2 Design

This cohort study investigated the accuracy of the automated detection of bowling events and ball counts in cricket using microtechnology devices. Participants were asked to perform normal bowling training to a batter in a net situation. Participants were then asked to perform a series of non-bowling events, including (i) run throughs ending in a single leg bound, and (ii) run throughs with a return throw. During data collection, each participant wore a GPS unit (MinimaxX S4, Catapult Innovations, Melbourne, Australia) in a small vest on their upper back. The GPS unit sampled at 10 Hz. The unit also housed tri-axial accelerometers, gyroscopes, and magnetometers, sampling at 100 Hz. Data collected by the microtechnology unit was processed secondarily using specifically designed software (Catapult Sprint, Catapult Innovations, Melbourne, Australia). The software produces fast bowling workload outputs when a pre-determined series of criteria are met in gyroscope, accelerometer and GPS data. All data collection was completed outdoors.

4.3.3 Methodology

The project was completed in three phases:

Phase 1 Bowling Events: Ten participants performed a total of 288 bowling events during net training sessions. Direct measures of bowling counts were completed in real-time by the researchers and verified using video notational analysis. Comparisons were made between the automated bowling counts obtained from the MinimaxX GPS units and the direct measures of bowling counts. The automatic detection of bowling counts is completed via an algorithm that marks a bowling action based on a series of events including; the detection of back foot contact defined by the directional change in the forwards accelerometer, and peaks in the rotation speed of the upper torso, greater than 500 degrees per second that is conditioned on a sufficient 'roll-like' rotation (Figure 10). Run up distance was measured from the bowlers set run up and ended with front foot contact. The average velocity of the run up was measured in the final 10 m and 5 m of the run up using a dual-beam light gate system (Swift Performance Equipment, Brisbane, Australia). The direct measures of run up distance and velocities were compared against the measures obtained from the MinimaxX GPS unit.

Phase 2: Non-Bowling: Ten participants performed a total of 160 non-bowling events during training sessions. The non-bowling events included: (i) a 20 m run through, without a ball being bowled, and (ii) a 15 m run to receive a ball and return a throw. The data recorded by the MinimaxX unit was analysed for false detections of bowling events.

Phase 3: Competition Events: Players also wore the MinimaxX devices during a series of 50 over matches. During competition, a total of 214 bowling events were recorded in five bowlers. True negative events were recorded when the following criteria were met; no bowling event was directly observed or recorded by the MinimaxX unit and a fast effort was recorded by the

MinimaxX unit. Fast efforts were defined as a running velocity greater than 5.1 m.s^{-1} or accelerations greater or equal to 2.78 m.s^{-2} [30, 73]. Previous studies have identified mean run up velocities in fast bowlers as being greater than $5.4 \pm 0.4 \text{ m.s}^{-1}$ which is in excess of the fast effort recorded by the unit [15].

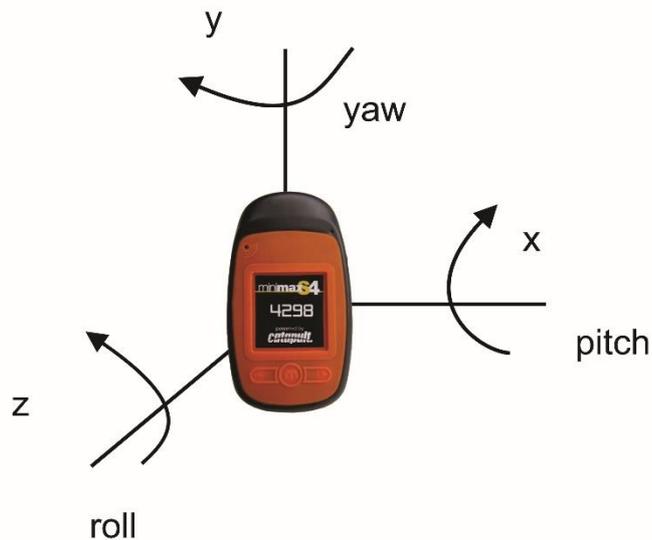


Figure 10. Axis' for yaw, pitch, and roll in the MinimaxX gyroscopes.

4.3.4 Statistical Analysis

Data were cross-validated to determine the accuracy of the bowling detection algorithm. The proportion of true positive and negative results, and false positive and negative results were also determined to allow the calculation of sensitivity and specificity values (Table 4). The relationship between the MinimaxX data and direct measures of balls bowled were assessed using the Pearson product moment correlation coefficient. MinimaxX and direct measure data were compared using independent t-tests and significance was set as $P < 0.05$. Run up distance and velocity measures from the direct measures and MinimaxX GPS unit were compared using the percentage bias and standard error of the estimate.

Table 4. Definition of true positive and negative, and false positive and negative bowling events recorded by the MinimaxX microtechnology unit.

Training			
<i>True Positive</i>	<i>True Negative</i>	<i>False Positive</i>	<i>False Negative</i>
Bowler bowled a ball and was recorded by the MinimaxX unit.	Bowler did not bowl a ball during a pre-determined cricket fielding activity and the MinimaxX unit detected no bowling event.	Bowler did not bowl a ball during a pre-determined cricket fielding activity and the MinimaxX unit detected a bowling event.	Bowler bowled a ball and was not recorded by the MinimaxX unit.
Competition			
<i>True Positive</i>	<i>True Negative</i>	<i>False Positive</i>	<i>False Negative</i>
Bowler bowled a ball and was recorded by the MinimaxX unit.	Meets all of the following criteria: <ul style="list-style-type: none"> - Bowler is not directly recorded as bowling a ball or detected as bowling a ball by the MinimaxX unit. - The MinimaxX unit records an effort of greater than 5.1 m.s⁻¹ OR an acceleration greater than 2.78 m.s⁻². 	MinimaxX unit records a ball being bowled when there is no direct measure of a ball being bowled.	Bowler bowled a ball and was not recorded by the MinimaxX unit.

4.4 Results

No differences ($P = 0.34$) were detected between the direct bowling counts and MinimaxX detection counts in either training or competition. A very strong correlation ($r = 0.99$) was identified between direct bowling counts and bowling counts recorded by the MinimaxX unit during both training and competition (Figure 11). No differences ($P = 0.19$) were detected between the direct non-bowling tasks and MinimaxX true negative events in training. A very strong correlation ($r = 0.99$) was observed between direct non-bowling tasks and MinimaxX true negative events in training.

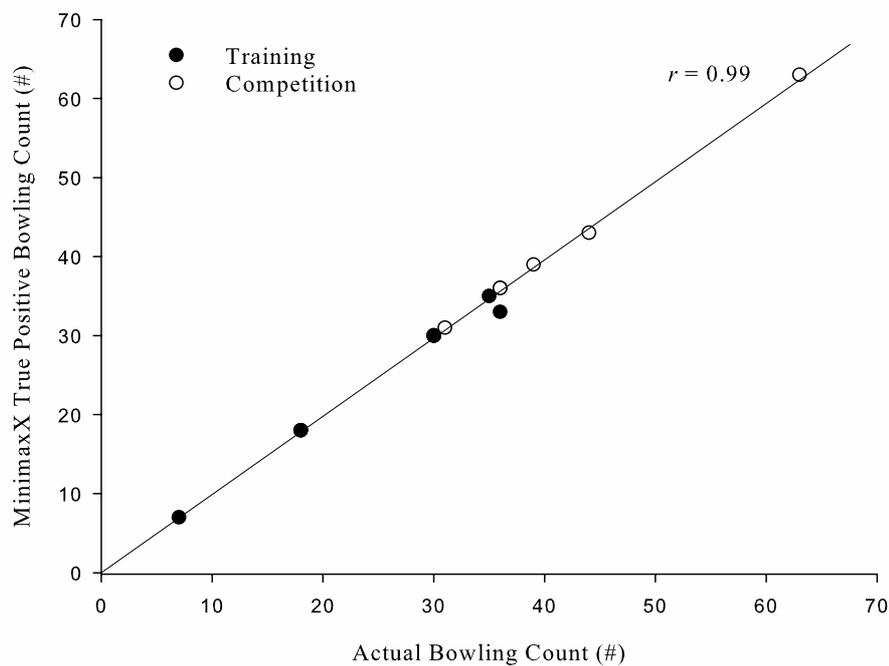


Figure 11. Comparison of direct measures of bowling count and MinimaxX bowling count during competition and training.

During training, both non-bowling and bowling events were observed to monitor the accuracy of the MinimaxX automated detection of bowling events and counts. A total of 448 events were observed during training, with detection of six false bowling events. Three of these events were categorised as false positive during dedicated bowling training (99.0% specificity) and three were classified as false negative during dedicated non-bowling fielding training (98.1% sensitivity) (Table 5).

Table 5. Accuracy of the MinimaxX microtechnology unit for the automated detection of bowling events during training.

		Ball bowled during training (as determined by direct bowling count)	
		Ball Bowled	Ball Not Bowled
Automated detection of ball bowled during training	Bowling Event Automatically Detected	True Positive = 285	False Positive = 3
	Bowling Event Not Automatically Detected	False Negative = 3	True Negative = 157
		Sensitivity = 99.0%	Specificity = 98.1%

During competition, a total of 345 events were observed, of which 214 were fast bowlers bowling a ball. The MinimaxX unit recorded a sensitivity of 99.5% for detecting bowling counts; only one fast bowling detection failure was recorded. The remaining events observed totalled 131, with 34 false positive bowling events and 97 true negative events being recorded by the MinimaxX unit (74.0% sensitivity) (Table 6).

Table 6. Accuracy of the MinimaxX microtechnology unit for the automated detection of bowling events during competition.

		Ball bowled during competition (as determined by direct bowling count)	
		Ball Bowled	Ball Not Bowled
Automated detection of ball bowled during competition	Bowling Event Automatically Detected	True Positive = 213	False Positive = 34
	Bowling Event Not Automatically Detected	False Negative = 1	True Negative = 97
		Sensitivity = 99.5%	Specificity = 74.0 %

Run up distance and velocity variables were recorded during the training bowling events. Run up distance outputs from the MinimaxX unit were shown to be very similar to the direct measure with a mean percentage bias of $0.80 \pm 0.06\%$ ($r = 0.90 \pm 0.02$). Run up velocity outputs were less accurate when compared with direct measures over the final 10 m ($-8.9 \pm 0.05\%$, $r = 0.88 \pm 0.03$) and 5 m ($-7.3 \pm 0.04\%$, $r = 0.90 \pm 0.03$) of the bowlers run up (Table 7).

Table 7. MinimaxX outputs and direct measurements for run up distance and velocity during training.

	Run Up Distance (m)		10 m Run Up Velocity (m.s ⁻¹)		5 m Run Up Velocity (m.s ⁻¹)	
	<i>MinimaxX</i>	<i>Direct</i>	<i>MinimaxX</i>	<i>Direct</i>	<i>MinimaxX</i>	<i>Direct</i>
Measures	20.3 ± 2.9	20.2 ± 2.6	5.8 ± 0.6	6.3 ± 0.6	6.0 ± 0.6	6.4 ± 0.6
Mean percentage bias (%)	0.80 ± 0.06		-8.91 ± 0.05		-7.29 ± 0.04	
Standard Estimate of Error	1.26		0.29		0.24	
Correlation, r	0.90 ± 0.02		0.88 ± 0.03		0.90 ± 0.03	

Measures and mean percentage data are mean ± SD. Correlation data are ± 95% CI.

4.5 Discussion

This study investigated the accuracy of automated bowling detection in both training and competition using a commercially available microtechnology unit (MinimaxX, Catapult Sports). The results demonstrated that the MinimaxX unit was very sensitive for detecting bowling counts during both training (99.0%) and competition (99.5%) in elite fast bowlers. In addition, the detection of non-bowling events during training and competition demonstrated that the MinimaxX unit also had high specificity, although with better performance in training (98.1%) than competition (74.0%). Overall, these findings suggest that the MinimaxX unit has exceptional specificity for detecting bowling counts during training and competition in elite fast bowlers.

During cricket training, players or coaches currently count the number of balls the bowler has performed in order to monitor the bowling workload. The reliance on the players and coaches to record balls bowled has a potential for error, particularly if the coach is distracted, or the bowler loses focus, becomes fatigued, or simply forgets to count. A system that can accurately and automatically record bowling counts is a valuable tool for the coach in order to monitor the workloads of fast bowlers. It should be noted that this becomes a greater issue in training than competition, as the exact number of true positives can be extracted from the scorecard during competition, providing an overall workload over the course of the match or day.

A reduction in specificity was observed during competition bowling counts in comparison to training counts. With the design of the bowling algorithm, greater

sensitivity often comes at the expense of specificity. That is, the criteria for the algorithm are diluted to ensure all bowling counts are captured. The lower specificity during competition is most likely due to the variability and random nature of competition in comparison with training, where more events are likely to meet the algorithm criteria of a ball being bowled. Bowlers are also known to bowl the ball when returning the ball back to the bowler or when returning a throw in the field, all of which could possibly result in a recorded bowling event. A high sensitivity in detecting bowling counts via the MinimaxX unit during competition is important, even if it slightly compromises specificity, as sensitivity has the potential to be accounted for by commercial manufacturers in future releases of the processing software. More specifically, bowling events in cricket are to a degree, predictable. Bowlers perform overs that consist of 6 balls, unless an illegal ball is bowled. Also, the time between balls is relatively predictable and consistent. This allows a reporting filter to potentially disregard any one off bowling events (false positives) recorded by the MinimaxX unit that do not fit the typical scenarios in which a ball is bowled. While this may result in an under-reporting of balls bowled when a bowler cannot complete a full over due to injury or rain, practically scientists can easily account for these rare events.

Fast bowling workloads have been linked to increased injury risk [22, 20, 21]. A dual workload threshold has been shown to influence injury risk in elite fast bowlers [20], whereby both under- and over-bowling increases the risk of injury. These findings suggest that a minimum volume of bowling is required to increase injury resilience, while excessive bowling loads may increase the risk of injury. However, a limitation of these previous studies is that the bowling workloads have neglected to take into account bowling intensity and/or effort of delivery. As a result, this broad definition of bowling

workload fails to account for the influence of bowling intensity and effort on the injury likelihood and/or resilience of the bowler. Measures of ball frequency, ball effort/velocity and subtle changes in bowling technique due to fatigue may contribute to both enhanced understanding of how bowling workload influences injury and how bowling workloads are prescribed to fast bowlers. In this study, warm up balls were not included in the data collection period. The authors acknowledge that future research design should account for bouts of lower intensity bowling. Whilst this study has highlighted how microtechnology units have the potential to further enhance bowling workload monitoring, further development in several output parameters is required to accurately illustrate ball to ball workloads.

4.6 Conclusions

The results of this study demonstrated that the MinimaxX unit was very sensitive for detecting bowling counts during both training and competition in elite fast bowlers. However, further refinements are required to account for the reduction in bowling detection specificity during competition. This study also investigated the detection of additional fast bowling workload parameters using the MinimaxX unit. Whilst the unit was accurate in detecting and measuring run up distance, further enhancements are required to accurately detect run up velocities.

4.7 Practical Applications

The introduction of microtechnology into cricket has allowed coaches to automatically detect bowling events in both training and competition. Automatically detecting bowling events will allow coaches to have an enhanced understanding of workloads

performed, even when they are not present at the time of the event. It is likely that this technology will enhance workload planning for fast bowlers.

The MinimaxX microtechnology unit offers adequate sensitivity and specificity for the automated detection of bowling counts during training activities. Although the sensitivity of automated bowling detection in competition is high, the unpredictable nature of match-play results in a greater number of false positives, with subsequent reductions in specificity during competition.

Cricket players cover lower relative distances compared with other team running sports such as Australian football and soccer [59]. The accurate detection of bowling events using microtechnology is likely to advance and add greater specificity to workload monitoring strategies in cricket, which may in turn improve bowling performance and reduce bowling injury rates [21].

4.8 Acknowledgements

We would like to thank the players and coaches of Cricket NSW. Special thanks is also extended to Michael Pappas who participated as a research assistant throughout this project.

Chapter 5: Variability of Player Load™, Bowling Velocity, and Performance

Execution in Fast Bowlers Across Repeated Bowling Spells

This study has been accepted for publication following peer review. Full reference details are:

McNamara DJ, Gabbett TJ, Chapman P, Naughton G, and Farhart P. Variability of PlayerLoad™, bowling velocity and performance execution in fast bowlers across repeated bowling spells. *International Journal Sports Physiology Performance*, 2015, 10 (8), 1009-1014.

5.1 Abstract

The use of wearable microtechnology to monitor the external load of fast bowling is challenged by the inherent variability of bowling techniques between bowlers. This study assessed the between bowler variability in Player Load™, bowling velocity, and performance execution across repeated bowling spells. Seven national level fast bowlers completed two, 6-over bowling spells at a batter during a competitive training session. Key dependent variables were: Player Load™ calculated with a MinimaxX microtechnology unit, ball velocity, and bowling execution based on a predetermined bowling strategy for each ball bowled. The between bowler CV, repeated measures ANOVA and SWC were calculated over the two repeated 6-over bowling spells and explored across 12-over, 6-over and 3-over bowling segments. From the sum of six consecutive balls, the between bowler CV for relative peak Player Load™ was 1.2% over the 12 over bowling spell ($P = 0.15$). During this 12 over period, bowling execution ($P = 0.43$) scores and ball velocity ($P = 0.31$) CV's were calculated as 46.0% and 0.4%, respectively. Player Load™ was found to be stable across the repeated bowling spells in the fast bowling cohort. Measures of variability and change across the repeated bowling spells were consistent with the performance measure ball velocity. The stability of Player Load™ improved when assessed relative to the individual's peak Player Load™. Only bowling execution measures were found to have high variability across the repeated bowling spells. Player Load™ provides a stable measure of external workload between fast bowlers.

5.2 Introduction

Cricket is a popular team sport that is played internationally. Cricket teams competing at elite levels consist of various player types that specialize in their position. Fast bowlers make up one of these specialist positions and have been identified as having greater physical workloads than other player types [30, 40]. The increasing variations in game formats now include multi-day, 50-over and 20-over cricket. Highly skilled fast bowlers in all game formats are characterized by having both greater sustainability in bowling velocity and accuracy than less skilled fast bowlers [44]. Bowling velocity and accuracy are routinely reported as performance measures in the fast bowling literature [44, 53]. Whilst there are rules and regulations that to an extent normalise the bowling action in cricket, there is inherent variability between fast bowling technique [74]. Commonly, fast bowlers compete across all game formats, despite the large disparities in acute and chronic workload requirements in both training and competition [30]. With the inherent variability in bowling technique between fast bowlers and the workload resulting from competition type, measures of fast bowling performance and more importantly, external workload need to remain stable across both shorter and longer bowling spells.

Previous research has identified the physiological characteristics of fast bowling spells [15]. Two, 6-over spells of fast bowling has been shown to increase rating of perceived exertion (peaking at 6.5 ± 0.8 arbitrary units), blood lactate concentrations (from 1.5 ± 0.3 to 5.0 ± 1.5 mmol.L⁻¹), and reduce blood glucose concentrations (from 6.3 ± 0.7 to 5.4 ± 0.4 mmol.L⁻¹) [14]. Variability in bowling accuracy was also monitored throughout the repeated bowling spells; CV for bowling accuracy of 39% for spell 1

and 43% for spell 2 were reported. The protocol scored the accuracy of balls bowled relative to a pre-determined target [44]. Despite showing that fast bowling is physically demanding, the influence of bowling duration and possibly fatigue on between over bowling accuracy and velocity remain unclear. Other studies have investigated bowling accuracy and velocity in elite and junior elite fast bowlers [44]. The researchers reported an uncoupling of ball velocity and accuracy amongst elite fast bowlers [44]. This non-linear relationship between ball velocity and accuracy suggests that these variables should be analyzed independently.

Fast bowling performance is largely influenced by environmental conditions. The nature of the pitch conditions, wind and even the country in which the match is played can influence the tactical decision-making of the fast bowler and therefore may change the skill execution requirements [75]. Previous research has identified that fast bowlers have greater levels of both accuracy and consistency when bowling at “good” lengths when compared with bowling at “full” lengths [44]. This suggests that functional accuracy or bowling execution in cricket is more important than simply bowling at a set target with no batter, particularly as bowling targets and bowling lengths are influenced greatly by match-play strategy for individual batters, and pitch conditions [75]. Measures of fast bowling performance need to be robust enough to account for the varying requirements of competition type, and also be stable enough to account for changes in performance.

Bowling workload has been identified as a contributor to injury likelihood [21]. To date, workload monitoring has been limited to counting the number of balls bowled by

fast bowlers during both competition and training. Cricket, along with other team sports have recently used GPS and associated microtechnology devices to monitor workloads in their athletes [30, 40, 73, 76]. Despite some issues with GPS data, specifically at high running velocities [77], the microtechnology housed within these same units (particularly the tri-axial accelerometer) has been shown to have good reliability in team sports [24]. To date, no study has explored the variability of the accelerometer technology housed within the widely used GPS units during repeated fast bowling spells among elite level cricketers.

To date, there have been no reports regarding external workload monitoring using microtechnology in fast bowling. As previously stated, fast bowlers inherently have variation in their fast bowling technique that may compromise the stability of the data reported by the microtechnology from athlete to athlete. In addition, fast bowling performance is defined at two levels, ball velocity and execution. Maintaining ball velocity at the expense of bowling execution would be considered a decline in fast bowling performance and not be a true representation of the demands of cricket fast bowling. With this in mind, the aims of this study were two-fold: (1) to document the variability of external workload measures between fast bowlers across bowling spells of varying duration, (2) to measure the variability and account for the influence of fatigue by measuring any significant change in fast bowling performance (velocity and execution) across these same bowling spells.

5.3 Methods

5.3.1 Subjects

Seven highly skilled fast bowlers (mean \pm SD age; 22.3 \pm 3.4 yr) participated in this study. At the time of the study each participant was competing at the first class or international level. All participants were free from injury or other medical conditions that would compromise participation. Participants received a clear explanation of the study, and written consent was obtained. The Australian Catholic University Human Research Ethics Committee approved all experimental procedures.

5.3.2 Design

In this repeated measures observational study, participants completed two separate bowling spells; each six overs in duration at batsmen in a cricket net setting. To simulate match conditions, a 15-minute active recovery was allocated between the six over spells.

5.3.3 Methodology

Data were collected during a routine training session directed by the coaching staff. Normal contest interaction between bowlers and batters was encouraged and bowlers self-selected their ball velocity. No slower balls were bowled during the data collection. Batsmen were both right and left-handed and rotated by the coaches every 10 minutes. All participants wore a GPS unit (MinimaxX S4, Catapult Innovations, Melbourne,

Australia) in a small vest on their upper back. The unit housed a tri-axial accelerometer, gyroscope, and magnetometer, sampling at 100 Hz.

Prior to each ball being bowled, the bowlers were required to nominate the area they intended to bowl to the current batter. Bowling areas were classified by two variables; bowling length and bowling line (Table 8). After each delivery, the bowlers were asked whether they executed the pre-planned bowl. A coach viewed, and cross-validated all execution responses reported by each participant. All balls were filmed for further validation by a camera located behind the stumps at the bowler's end of the pitch and a second camera behind the net at the batter's end of the pitch. A set of 20 cm lines on the cricket nets distinguished line and length. A score of 2 was allocated for correctly executed bowling events and a score of 1 was allocated to balls that were not executed.

Bowling velocity was measured directly for each ball bowled using a hand held speed gun accurate to $\pm 3\%$ (Stalker Pro II, Stalker Sports Radar, Plano, Texas). Scores of peak Player Load™ were measured by the MinimaxX unit and extracted from the commercially available software (Sprint, Catapult Innovations, Melbourne, Australia) for each ball bowled. Player Load™ is an arbitrary measure based on the accelerometer outputs obtained from the MinimaxX unit. Specifically, Player Load™ is a modified vector magnitude, calculated 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 axis) and divided by 100.(13) Ball velocity and Player Load™ scores were reported as raw data and as a score relative to the participant's maximum ball velocity and Player Load™ over the entire 12-overs.

With the aim of tracking variability changes over the course of different bowling spell lengths, data were divided into the following for analysis; entire 12-overs, first 6-overs, second 6-overs, overs 1 to 3, overs 4 to 6, overs 7 to 9 and overs 10 to 12. Scores for ball velocity, Player LoadTM and execution were summed over 3 and 6 consecutive balls to provide an accumulated score for analysis. Ball velocity and Player LoadTM were also analyzed for each individual ball.

Table 8. Bowling area classification.

<i>Bowling Length</i>	<i>Bowling Line</i>
a. Short	a. >30 cm outside off-stump
b. Good	b. Between off-stump and 30 cm
c. Full	outside off-stump
	c. Middle and leg stump
	d. Outside leg stump

Line and length was observed by researcher and confirmed by coaching staff. All balls were filmed for further validation and a set of 20 cm lines on the cricket nets distinguished line and length.

5.3.4 Statistical Analysis

Data were tested for normality prior to analysis using a Shapiro Wilks test. Bowling execution, ball velocity and Player LoadTM results were analyzed using a custom made Excel spreadsheet (Microsoft, Redmond, USA) [78, 79]. All data were log transformed and the CV with 90% CI calculated. A CV less than 10% has previously been described

as an indicator of acceptable agreement [80]. The CV is the variation of bowling execution, ball velocity or Player Load™ expressed as a percentage of the average. Repeated measures ANOVA was completed on all bowling spells and significance was set at $P \leq 0.05$. ANOVA's were conducted using SPSS (version 21.0, IBM Corporation, USA). The SWC was also determined for each bowling segment. The SWC was calculated as 0.2 x the 'between bowler' standard deviation.

5.4 Results

The CV with 90% CI and P values for bowling execution, ball velocity and peak Player Load™ are shown in Table 10 and Table 11, respectively. Mean ball velocity was measured as 124.2 ± 6.1 km/hr across all participants during the 12-overs (Table 9). When measuring relative peak Player Load™ as the sum of scores over 6 balls (1-over), the CV was measured as 1.9% (1.7-2.1) with a SWC of 2.4 arbitrary units across the 12-overs ($P = 0.15$). Over the same 12-over period when summing the scores for 6 consecutive balls, the CV and SWC were 0.4% (0.4-0.5) and 0.6 km/hr, respectively for relative ball velocity ($P = 0.31$) and 46.0% (41.0-53.0) and 2.4 arbitrary units , respectively, for bowling execution ($P = 0.43$).

Table 9. Mean and Standard Deviation for bowling execution, ball velocity and peak Player Load™.

Overs	<i>Relative Ball Velocity (%)</i>		<i>Relative Peak Player Load™ (%)</i>		<i>Ball Velocity (km/h)</i>		<i>Peak Player Load™(AU)</i>		<i>Execution (Score)</i>	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
12 overs	94.0	3.3	79.7	7.7	124.2	4.3	5.4	0.5	1.7	0.5
1 st 6 overs	94.0	2.5	79.2	7.4	124.2	3.3	5.4	0.5	1.6	0.5
2 nd 6 overs	94.0	3.7	80.2	7.6	124.2	4.8	5.5	0.5	1.7	0.5
Overs 1 – 3	93.5	2.3	78.0	7.8	123.5	3.1	5.3	0.5	1.6	0.5
Overs 4 – 6	94.4	2.4	80.5	6.2	124.8	3.1	5.5	0.4	1.6	0.5
Overs 7 – 9	94.5	2.8	81.0	7.2	124.9	3.7	5.5	0.5	1.7	0.5
Overs 10 – 12	92.9	4.4	79.4	6.6	122.8	5.9	5.4	0.5	1.7	0.5

Standard deviation (SD). Arbitrary units (AU)

When summing the scores for 6 consecutive balls, ball velocity CV and SWC over the first 6-over bowling spell ($P = 0.06$) was 0.4% (0.4-0.5) and 0.6 km/hr, and 0.4% (0.3-0.5) and 0.6 km/hr across the second 6-over bowling spell ($P = 0.33$). Relative peak Player Load™ CV and SWC over the first 6-over bowling spell ($P = <0.00$) was 0.9% (0.8-1.1) and 2.4 arbitrary units and 1.0% (0.9-1.3) and 2.4 arbitrary units over the second 6-over bowling spell ($P = 0.42$) when summing the scores for 6 consecutive balls. Across these same bowling spells, bowling execution CV and SWC was 28.0 (23.0-34.0) and 7.1 arbitrary units in the first 6-over bowling spell ($P = 0.31$), and 21.0 (18.0-25.0) and 6.4 arbitrary units across the second 6-over bowling spell ($P = 0.77$).

Table 10. Between fast bowler variation in performance over 12 overs - sum of scores over 6 consecutive balls and 3 consecutive balls.

Sum of scores over 6 consecutive balls (1 over)															
Overs	<i>Relative Ball Velocity</i>			<i>Relative Peak Player LoadTM</i>			<i>Ball Velocity</i>			<i>Peak Player LoadTM</i>			<i>Execution</i>		
	CV (%)	<i>P</i>	SWC	CV (%)	<i>P</i>	SWC	CV (%)	<i>P</i>	SWC	CV (%)	<i>P</i>	SWC	CV (%)	<i>P</i>	SWC
12 overs	0.3 (0.3-0.4)	0.31	0.8	1.9 (1.7-2.1)	0.15	3.3	0.4 (0.4-0.5)	0.31	0.6	1.2 (1.1-1.4)	0.15	2.4	46.0 (41.0-53.0)	0.43	6.8
1 st 6 overs	0.2 (0.2-0.3)	0.06	0.8	1.6 (1.4-2.0)	0.01	3.4	0.2 (0.2-0.2)	0.06	0.6	0.9 (0.8-1.1)	0.03	2.4	28.0 (23.0-34.0)	0.31	7.1
2 nd 6 overs	0.4 (0.3-0.4)	0.34	0.8	1.8 (1.6-2.3)	0.42	3.2	0.4 (0.3-0.5)	0.33	0.6	1.0 (0.9-1.3)	0.42	2.4	21.0 (18.0-25.0)	0.77	6.4
Overs 1 – 3	0.3 (0.2-0.3)	0.04	0.9	2.1 (1.7-2.8)	>0.00	3.2	0.3 (0.2-0.4)	0.04	0.6	1.2 (1.0-1.6)	>0.00	2.4	32.0 (26.0-43.0)	0.18	7.3
Overs 4 – 6	0.1 (0.0-0.1)	0.90	0.7	0.7 (0.5-0.9)	0.91	3.6	0.1 (0.1-0.1)	0.90	0.5	0.4 (0.3-0.5)	0.91	2.5	27.0 (21.0-36.0)	0.55	6.9
Overs 7 – 9	0.3 (0.2-0.4)	0.17	0.7	1.4 (1.1-1.9)	0.11	3.1	0.3 (0.3-0.4)	0.17	0.4	0.8 (0.631.1)	0.11	2.7	20.0 (16.0-26.0)	0.55	6.7
Overs 10 – 12	0.4 (0.3-0.5)	0.49	0.9	1.4 (1.1-1.9)	0.45	3.5	0.4 (0.3-0.5)	0.52	0.7	0.8 (0.6-1.1)	0.46	2.2	22.0 (17.0-29.0)	0.85	6.3
Sum of scores over 3 consecutive balls															
12 overs	0.4 (0.4-0.5)	0.26	0.9	1.4 (1.3-1.5)	0.13	3.4	0.5 (0.2-0.5)	0.26	0.7	2.7 (2.4-3.1)	0.13	2.5	70.0 (64.0-76.0)	0.44	8.4
1 st 6 overs	0.3 (0.3-0.4)	0.12	0.8	1.2 (1.1-1.4)	0.01	3.5	0.4 (0.3-0.4)	0.12	0.8	2.4 (2.1-2.8)	0.01	2.5	76.0 (67.0-87.0)	0.30	8.4
2 nd 6 overs	0.5 (0.4-0.6)	0.25	0.9	1.4 (1.2-1.6)	0.40	3.3	0.5 (0.5-0.6)	0.25	0.7	2.7 (2.4-3.1)	0.40	2.5	66.0 (59.0-76.0)	0.64	8.4
Overs 1 – 3	0.3 (0.3-0.4)	0.08	0.9	1.5 (1.3-1.8)	>0.00	3.3	0.4 (0.3-0.4)	0.08	0.7	3.0 (2.5-3.6)	>0.00	2.6	89.0 (75.0-110.0)	0.18	8.0
Overs 4 – 6	0.3 (0.2-0.3)	0.53	0.7	0.7 (0.6-0.9)	0.61	3.6	0.3 (0.2-0.3)	0.54	0.6	1.4 (1.2-1.7)	0.61	2.5	70.0 (59.0-85.0)	0.58	8.8
Overs 7 – 9	0.4 (0.3-0.5)	0.13	0.8	1.2 (1.0-1.4)	0.20	3.1	0.4 (0.3-0.5)	0.13	0.5	2.3 (1.9-2.8)	0.20	2.8	68.0 (57.0-82.0)	0.39	8.5
Overs 10 – 12	0.5 (0.5-0.7)	0.40	1.0	1.1 (1.0-1.4)	0.36	3.5	0.6 (0.5-0.7)	0.4	0.8	2.3 (1.9-2.8)	0.36	2.3	72.0 (61.0-87.0)	0.84	8.3

Coefficient of variation and 90% confidence interval (CV%). *P*: Repeated measures ANOVA. SWC: smallest worthwhile change (0.2 x between bowler standard deviation).

Table 11. Between fast bowler variation in performance over 12 overs – individual ball score.

Overs	<i>Relative Ball Velocity</i>			<i>Relative Peak Player LoadTM</i>			<i>Ball Velocity</i>			<i>Peak Player LoadTM</i>		
	CV (%)	<i>P</i>	SWC	CV (%)	<i>P</i>	SWC	CV (%)	<i>P</i>	SWC	CV (%)	<i>P</i>	SWC
12 overs	0.8 (0.8-0.8)	0.30	0.9	2.4 (2.3-2.5)	0.29	3.0	0.8 (0.8-0.8)	0.30	1.0	6.4 (6.1-6.8)	0.29	3.8
1 st 6 overs	0.6 (0.5-0.7)	0.25	0.8	2.2 (2.1-2.4)	0.11	3.0	0.6 (0.6-0.7)	0.25	0.9	6.0 (5.6-6.5)	0.11	3.8
2 nd 6 overs	0.9 (0.8-1.0)	0.28	0.9	2.5 (2.3-2.7)	0.44	3.1	0.9 (0.8-1.0)	0.28	1.1	6.4 (6-6.9)	0.44	3.7
Overs 1 – 3	0.6 (0.5-0.7)	0.11	0.8	2.3 (2.1-2.6)	0.04	2.9	0.5 (0.5-0.6)	0.11	1.0	6.3 (5.7-7)	0.04	3.6
Overs 4 – 6	0.6 (0.5-0.7)	0.55	0.8	1.9 (1.7-2.1)	0.42	3.0	0.5 (0.5-0.6)	0.55	0.9	5.1 (4.6-5.7)	0.42	4.0
Overs 7 – 9	0.6 (0.5-0.7)	0.13	0.7	2.3 (2.1-2.6)	0.35	3.5	0.6 (0.5-0.7)	0.14	0.9	6.1 (5.5-6.8)	0.35	3.7
Overs 10 – 12	1.0 (0.9-1.1)	0.40	1.1	2.0 (1.8-2.2)	0.38	2.7	1.0 (1.0-1.1)	0.40	1.3	5.4 (4.9-6.0)	0.38	3.8

Coefficient of variation and 90% confidence interval (CV%). *P*: Repeated measures ANOVA. SWC: smallest worthwhile change (0.2 x between bowler standard deviation).

5.5 Discussion

This study investigated the between bowler variability of external workload measures from wearable microtechnology in seven elite performing fast bowlers. Fast bowling performance measures including bowling execution and ball velocity were also measured for change and variability across repeated fast bowling spells. The primary findings of this study were that Player Load™ remained stable across bowling spells of varying length despite the inherent variability between fast bowling techniques. Variability in Player Load™ improved when measures were observed relative to the individual's peak scores. Between bowler ball velocity had acceptable variability over both 6 and 12-over bowling spells, while bowling execution had large variation between elite cricket fast bowlers.

When assessing individual balls bowled over the 12-overs, Peak Player Load™ demonstrated noticeably less variability when observed as a score relative to the individual's maximum. Player Load™ More specifically, across 12-overs the relative peak Player Load™ CV was 2.4% (2.3-2.5) vs. the peak Player Load™ CV of 6.4% (6.1-6.8) for individual balls bowled. While it is likely that individual bowling technique influenced absolute Player Load™ measures, the observed CV for absolute measures of Player Load™ were still low. Relative measures of peak Player Load™ may therefore offer a better method of monitoring fast bowling cohorts for bowling workload rather than the absolute value. Relative peak Player Load™ values may provide an additional method of workload monitoring in fast bowlers to supplement the current ball count method [37]. Future investigations of fast bowling workload-monitoring practices are required. In other team sports (e.g. Australian Football), Player

Load™ has been identified as having good reliability for the monitoring of workload across various bouts of activity [24].

No change in Player Load™ measures were observed across any bowling spell when assessing individual balls. This finding was consistent with the findings from the more traditional fast bowling performance measures (e.g. ball velocity) across bowling spells. Player Load™ increased in the first 3 and 6-over bowling spells when assessing Player Load™ as the sum of 3 consecutive balls, and the accumulation of scores across 1-over. The ability to detect change and the reduction of CV within the consecutive ball Player Load™ measure compared to the Player Load™ of individual balls may be explained by a filtering effect in the Player Load™ scores. Further investigation may be required to optimise the post-processing of Player Load™ outputs for analysis from fast bowlers, specifically when observing individual balls.

The bowling execution in this study exhibited CV measures of 28.0% and 21.0% over the first and second 6-over bowling spells. This occurred despite the execution scores being summed over 6 balls. These high CVs are consistent with previous studies of similar sample size and bowling duration that have investigated bowling accuracy (39% and 43%).(6) The authors acknowledge that the CV reported in this study for bowling execution is high. This is possibly attributed to the inability of fast-bowlers to consistently execute, although no significant change in performance execution was detected. It is also acknowledged that a limitation of the present study is the small sample size. It is likely that this small sample size has contributed to the high CV measures. Small sample sizes are often a challenge in elite settings due to the limited number of elite performers. In the case of this study, the participants represented over 60% of the fast bowlers in the entire squad of international level fast bowlers and 90% of the available

fast bowlers during the data collection period. All data were collected in the first half of the Australian domestic season. Although this study had a small sample size, the results suggest that future studies of bowling accuracy and execution across fast bowling cohorts should be interpreted with caution. Furthermore, future studies would benefit from a collaborative approach in order to increase the sample of elite participants across numerous professional teams.

The bowling execution CV results in this study draw parallels with previous fast bowling accuracy measures [53]. The large dispersion in bowling accuracy and execution scores reported in this and previous research highlights the careful consideration required when analyzing accuracy measures across a fast bowling cohort. Although the CV in this paper is high, the experimental design does provide relevant feedback to coaching staff and with further refinement may adequately track bowling performance over a bowling spell. Previous accuracy protocols have scored the accuracy of fast bowlers when bowling “short”, “good” and “full” lengths with scores for accuracy being highest in the centre of the bowling target and reduced along the radius of the target [44]. In these studies, the bowling target was relative to the stumps at the end of the pitch. Other studies have used targets on the cricket pitch and reported scores based on the line and length of the ball [53]. To an extent, this accounts for the variation in the bounce of the ball that may influence the bowler’s ability to hit targets at the end of the pitch. However, measurement of accuracy in this manner may not be the best measure for fast bowling performance, as bowlers are required to bowl a wide range of lengths and lines depending on the batter they are bowling to and the strategy they are trying to execute during competition. Whilst accuracy scores have been able to distinguish between highly skilled and less skilled fast bowlers [44], such protocols are likely to be cumbersome and unnecessary in the routine practice of elite fast bowlers. We suggest that a simplified method of bowling

execution whilst bowling to a batter is a far more practical and meaningful measure amongst elite fast bowlers. Finally, feedback from additional markings that are placed on or at the end of cricket pitches may provide atypical feedback for the bowler, positively and/or negatively influencing performance measures. Refinements in ball tracking technology may provide non-invasive and more accurate and reliable measures of accuracy/execution. With careful consideration, bowling accuracy/execution should be accounted for when monitoring fast bowling performance.

Literature has reported that senior fast bowlers are able to bowl at velocities of 127 km/h [46]. The present study has only observed fast bowling velocities during training settings. We recommend the determination of bowling velocity and Player Load™ CV's during match-play over individual bowling spells and the course of a competition day, as fatigue may have a greater impact on variance between bowlers and change across bowling spells under these conditions. Ball velocity data are readily made available in the public domain (cricket broadcasters), although any research would require a review of the accuracy of the measurement tools used by the broadcasters. Bowling velocity has been used to determine both bowling performance and as a measure of bowling effort and or intensity [15]. The CV measures of this paper suggest that when injury free, this may be an appropriate measure across elite performers.

This is the first study to observe the variance of microtechnology outputs in fast bowlers across bowling spells of varying duration. A measure of external load (i.e. Player Load™), was shown to be stable across fast-bowlers. Player Load™ measures were consistent with ball velocity

measures, which is routinely used to monitor bowling intensity. The objectively measured Player Load™ has the ability to further advance workload monitoring in cricket fast bowlers.

5.6 Conclusion

This paper provides insight into the between-bowler variation of external workload, measured with microtechnology, over the duration of repeated bowling spells in a competitive training environment. The variability and measures of change in microtechnology outputs across repeated bowling spells were consistent with ball velocity. Whilst the bowling velocity and Player Load™ CV measures would be considered appropriate to be used in future cricket research, measures of bowling execution may require greater sample sizes and/or careful interpretation, before including in routine fast bowling analyses. Bowling velocity, more so than bowling execution may provide greater stability across a fast bowling cohort in the interpretation of fast bowling performance. Player Load™ values, when expressed relative to peak scores, exhibit an adequate level of stability across bowling spells.

5.7 Practical Applications

Microtechnology outputs such as Player Load™, offer a stable measure of external workload between fast bowlers and across bowling spells of varying duration. When expressed relative to peak Player Load™, individual Player Load™ is a more stable measure of external workload between fast bowlers than the absolute value.

Fast bowling velocity remains a stable measure of performance in elite fast bowlers. The sustainability of bowling velocity in aspiring elite fast bowlers could be included in goal setting and coaching. This also provides a potential method of measuring the bowling intensity of separate bowling workloads.

Bowling execution measures in small sample sizes of elite fast bowlers offer an unstable measure of performance. This is consistent with previous fast bowling accuracy measures.

5.8 Acknowledgements

No financial assistance was provided for this project.

Chapter 6: Relationship between wearable microtechnology device variables and cricket fast bowling intensity

This study has been submitted for review with the International Journal Sports Physiology Performance. Full reference details are:

McNamara DJ, Gabbett TJ, Blanch P, and Kelly L. Relationship between wearable microtechnology device variables and cricket fast bowling intensity. 2016. *International Journal Sports Physiology Performance*, In review.

6.1 Abstract

To date, the monitoring of fast bowling workloads across training and competition environments has been limited to counting total balls bowled. However, bowling at faster velocities is likely to require greater effort while also placing greater load on the bowler. This study investigated the relationship between prescribed effort and microtechnology outputs in fast bowlers to ascertain whether the technology could provide a more refined measure of workload. Twelve high performing fast bowlers (mean \pm SD age; 20.3 \pm 2.2 yr) participated in this study. Each bowler bowled 6 balls at prescribed bowling intensities of 60%, 70%, 85% and 100%. The relationship between microtechnology outputs, prescribed intensity and ball velocity were determined using polynomial regression. Very large relationships were observed between prescribed effort and ball velocity for peak Player LoadTM ($R = 0.83 \pm 0.19$ and 0.82 ± 0.20). The Player LoadTM across lower ranges of prescribed effort exhibited higher CV [60% = 19.0 (17.0 – 23.0)%] while the CV at higher ranges of prescribed effort was lower [100% = 7.3 (6.4 - 8.5)%]. Routinely used wearable microtechnology devices offer opportunities to examine workload and intensity in cricket fast bowlers outside the normal metrics reported. They offer a useful tool for strength and conditioning coaches to prescribe and monitor bowling intensity and workload in elite fast bowlers.

6.2 Introduction

Cricket, like many other popular international team sports, requires varying player types to perform very specific roles within the team. One of these roles within cricket is fast bowling. Fast bowlers are required to bowl at high ball velocities to opposition batters. Fast bowling has been associated with greater injury risk in comparison to other playing activities [22].

Fast bowling injury rates have been associated with both poor technique and bowling workloads [22, 47, 20]. A current method of monitoring the preparedness of fast bowlers includes both planning and reviewing the chronic (28 day average) vs. acute (7 day average) bowling loads. Although this method provides a general view of the preparedness of the fast bowler, it fails to account for the range of bowling intensities across sessions, their contribution to the overall load and ultimately, preparedness. While it is possible that coaches could subjectively identify periods of high bowling intensity, this can become relatively unstructured and fails to account for the individual bowler's fatigue responses to workloads. The method of monitoring bowling speed is a possible indicator of intensity, although practical limitations exist with this method. Individual fast bowlers are routinely spread across varying training nets or often competing at different locations; considerable resources are required to allow sport scientists to collect this data. Understandably, bowling velocity also acts as a performance indicator and provides meaningful data to coaches, particularly in match-play. While bowling velocity may provide a simple option for measuring intensity in a single controlled bowling session, when multiple bowlers are performing across various sessions and locations this process becomes somewhat laborious and difficult.

Various team sports use microtechnology devices to monitor external workload [24, 18, 25]. Microtechnology manufacturers also use accelerometers housed within commercially available GPS, devices to provide additional information on external loads [28, 26]. Accelerometer load has been shown to have acceptable stability across 3, 6 and 12 over bowling spells [81]. In addition to a tri-axial accelerometer, gyroscopes capable of detecting rotation about the yaw, pitch and roll axes are also housed within certain commercially available microtechnology units. Microtechnology has been used successfully to detect fast bowling events in elite cricketers [46]. This technology allows for retrospective analysis of external workload in large groups of athletes and does not require a coach or sport scientist to be present at the time of data collection. This method of load monitoring is important to cricket as players often train in de-centralized programs or are required to participate for various domestic teams across the world within the same competitive year. These units are not limited to training environments and are commonly worn during competition in many sports including cricket.

If this technology was capable of capturing fast bowling intensity, it would provide an opportunity to further advance the workload monitoring of elite fast bowlers during training and competition. This would allow insightful data for the prescription of individual fast bowling workloads. With this in mind, the aim of this study was to assess the relationship between prescribed bowling intensities, bowling velocity and data outputs from wearable microtechnology during a training environment to ascertain whether the technology could provide a more refined measure of workload and bowling intensity.

6.3 Methods

6.3.1 Experimental Approach to the Problem

This cohort study required participants to complete six deliveries in four categories of effort; (1) warm up (~60%), (2) light intensity (~70%), (3) match-play (~85%), and (4) maximal effort (~100%). All bowlers completed the bowling protocol in the same pre-determined order. To help represent the varying bowling lengths in cricket match-play, during the 85% (match-play) and 100% (maximal effort) overs, each player bowled two short balls, two full balls and two good length balls. No balls, wides, balls bowled with illegal actions and those that were not performed at the prescribed bowling length were excluded from analyses. This data were monitored and confirmed by a cricket coach. Measures of bowling intensity included a subjective measure of prescribed effort, bowling velocity and outputs from wearable microtechnology.

6.3.2 Subjects

Twelve elite fast bowlers (mean \pm SD age; 20.3 \pm 2.2 yr) participated in this study. At the time of the study all players were participants in a national level high performance camp. All participants were free from injury or other medical conditions that would compromise participation. Participants received a clear explanation of the study, and written consent was obtained. The Australian Catholic University Human Research Ethics Committee approved all experimental procedures.

6.3.2 Bowling Intensity

6.3.2.1 Ball Velocity

Ball velocity was measured for each delivery using a high performance sports radar gun accurate to $\pm 3\%$ (Stalker Pro, Stalker Sports Radar, Piano, Texas) positioned at the batters end of the cricket pitch. No bowling velocity feedback was provided to the bowlers. A relative ball velocity score was calculated as a percentage of the individual bowlers peak ball velocity across the 24 balls bowled.

6.3.2.2 Microtechnology

Data from the accelerometers and gyroscopes embedded in the microtechnology device (MinimaxX S4, Catapult Innovations, Melbourne, Australia) were extracted from the commercially available software (Sprint, Catapult Innovations, Melbourne, Australia) for each ball bowled. Both the accelerometers and gyroscopes collected data at 100 Hz. Player Load™ and the resultant accelerometer vector were calculated from each of the X, Y and Z vectors. In this study, Player Load™ was calculated as the root sum of squares of the delta acceleration. Roll (x-axis – lateral flexion during bowling) and yaw (z-axis – rotation at the thoracic spine during the bowling action) gyroscope velocity outputs were collected from the microtechnology device for each ball bowled. Peak measures of Player Load™, accelerometer resultant, yaw velocity and roll velocity during the delivery stride were used for analysis of each ball. A percentage relative to the individual bowlers peak score across the 24 balls bowled was calculated for each ball across all variables. Measures of roll have previously been used to distinguish fast bowling events within cricket practice and competition [46].

6.3.3 Statistical Analyses

Residuals were normally distributed. The relationship between the microtechnology outputs and both prescribed effort and ball velocity were analyzed using polynomial regression in SPSS (IBM Corp, Armonk, USA) and expressed as R. These relationships were described as trivial (0.0 – 0.1), small (0.1 – 0.3), moderate (0.3 – 0.5), large (0.5 – 0.7), very large (0.7 – 0.9) or nearly perfect (0.9 – 1.0) [78]. A custom Microsoft Excel spreadsheet (Microsoft, Redmond, USA) was used to calculate the CV with 90% CI to describe the variability across intensity levels.

6.4 Results

Peak Player Load™ showed very large relationships ($R = 0.83 \pm 0.19$) with prescribed effort for each ball bowled (Table 12, Figure 12). Relative ball velocity was also associated with peak Player Load™ ($R = 0.82 \pm 0.20$) for each ball bowled (Table 12, Figure 12). Peak yaw ($R = 0.58 \pm 0.36$), roll ($R = 0.73 \pm 0.27$) and resultant accelerometer ($R = 0.64 \pm 0.33$) data all showed large to very large relationships with relative ball velocity for each ball bowled (Table 12).

Table 12. Relationship between bowling effort, ball velocity, and microtechnology outputs.

<i>Prescribed Effort</i>		<i>Ball Velocity</i>	
<i>Relationship</i>	<i>R</i>	<i>Relationship</i>	<i>R</i>
Resultant max %	0.71 ± 0.28 <i>Very Large</i>	Resultant max %	0.64 ± 0.33 <i>Large</i>
Player Load™ max %	0.83 ± 0.19 <i>Very Large</i>	Player Load™ max %	0.82 ± 0.20 <i>Very Large</i>
Roll max %	0.80 ± 0.21 <i>Very Large</i>	Roll max %	0.73 ± 0.27 <i>Very Large</i>
Yaw max %	0.56 ± 0.37 <i>Large</i>	Yaw max %	0.58 ± 0.36 <i>Large</i>

Polynomial regression \pm 90% CI and descriptor.

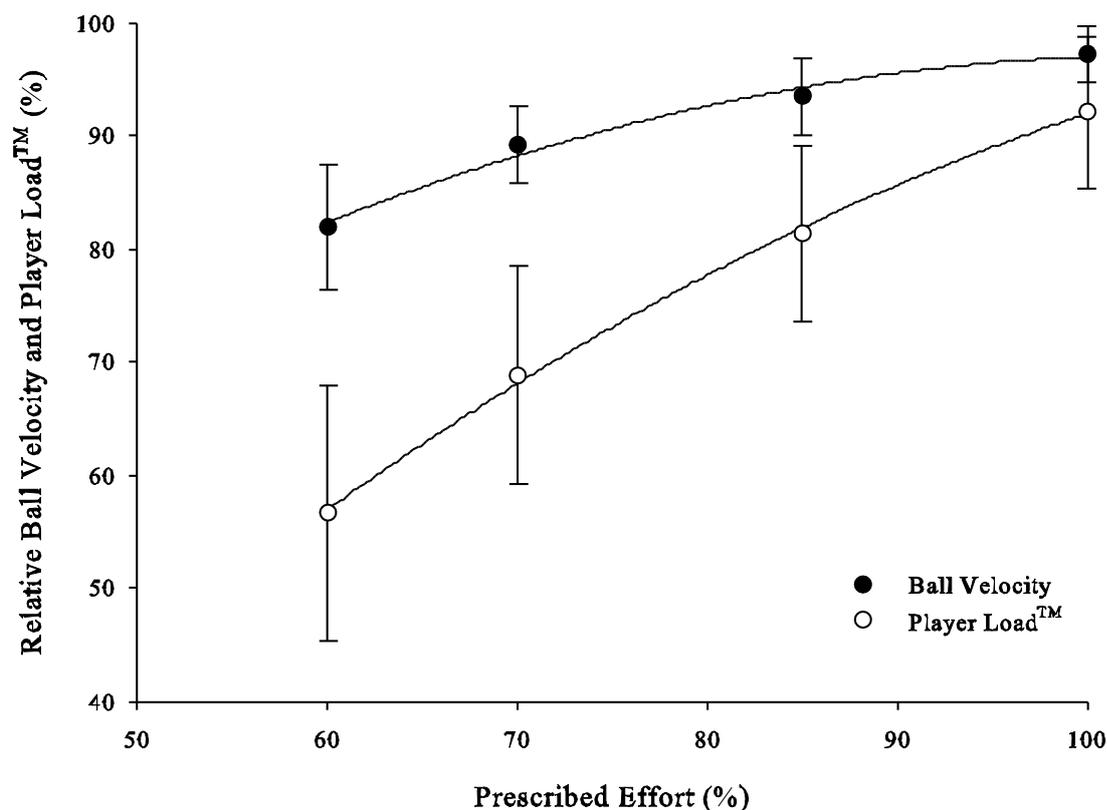


Figure 12. Mean \pm Standard Deviation of relative ball velocity and relative Player Load™ vs. prescribed effort.

Measures of CV in Peak Player Load™ were 19.0% (17.0 – 23.0), 14.0% (12.0 – 16.0), 9.6% (8.4 – 11.0) and 7.3% (6.4 – 8.5) across the prescribed 60% (warm up), 70% (light intensity), 85% (match-play) and 100% (maximal effort) bowling intensities (Table 13), suggesting that as bowling effort increased, measures of intensity began to stabilize. Relative ball velocity followed the similar trend across prescribed bowling intensities with CV of 6.6% (5.8 – 7.7), 3.8% (3.4 – 4.4), 3.6% (3.2 – 4.2) and 2.6% (2.3 – 3.0) across the four prescribed bowling intensities (Table 13).

Table 13. Mean and coefficient of variation across prescribed bowling intensities.

Variable		<i>Bowling Intensity %</i>			
		60%	70%	85%	100%
Peak Roll %	<i>Mean</i>	64.4%	74.9%	88.0%	93.2%
	<i>CV (%)</i>	16.0 (14.0 – 18.0)	11.0 (10.0 – 13.0)	11.0 (9.3.0 – 12.0)	6.1 (5.4 - 7.1)
Peak Accelerometer resultant %	<i>Mean</i>	57.0%	72.2%	81.0%	86.4%
	<i>CV (%)</i>	21.0 (19.0 – 24.0)	17.0 (15.0 – 19.0)	12.0 (10.0 – 13.0)	12.0 (10.0 – 13.0)
Peak Player Load™ %	<i>Mean</i>	56.7%	68.8%	81.4%	92.1%
	<i>CV (%)</i>	19.0 (17.0 – 23.0)	14.0 (12.0 – 16.0)	9.6 (8.4 – 11.0)	7.3 (6.4 - 8.5)
Peak Yaw %	<i>Mean</i>	72.8%	82.6%	91.2%	93.3%
	<i>CV (%)</i>	22.0 (19.0 – 26.0)	16.0 (14.0 – 18.0)	10.0 (9.1 – 12.0)	8.4 (7.4 - 9.7)
Relative Ball Velocity %	<i>Mean</i>	81.9%	89.2%	93.5%	97.2%
	<i>CV (%)</i>	6.6 (5.8 - 7.7)	3.8 (3.4 - 4.4)	3.6 (3.2 - 4.2)	2.6 (2.3 – 3.0)

Coefficient of variation (CV%) and 90% CI.

6.5 Discussion

This study (1) examined the relationship between prescribed bowling effort, bowling velocity and the outputs from a microtechnology device, and (2) developed a novel and meaningful method of reporting fast bowling effort from microtechnology devices. The results of this study demonstrate a good relationship between prescribed bowling effort and both bowling velocity and Player Load™ results. Data were reported as percentages relative to maximal efforts of individual fast bowlers, which accounts for individual variations in technique and bowling velocities, and is easily processed by cricket coaches. Practically, calibrating the percentage effort of each ball to a recent effort within a significant competition match provides both context and meaningful data for coaches and support staff.

To date, the measurement of bowling workload has been limited to the more simple method of bowling counts [46, 21, 20]. This presents a simple definition of total workload, but may not account for the variability and significance of higher effort bowling from session to session and game to game. Intuitively, the intensity of individual bowling sessions will have a significant influence on the bowlers load, and may have an influence on the physical status and fatigue of bowlers. As such, bowling intensity is likely to influence the preparation of fast bowlers for various levels of competition.

The large variability in the microtechnology metrics at sub maximal intensities can be explained by the greater scope for variability at lower or submaximal intensities (Table 13). Importantly, the ball velocity, measured with a routinely used radar gun, also exhibited an increased variability at lower intensities. We acknowledge that the microtechnology output exhibit greater variability than ball velocity and should be considered a limitation of the

technology. However, this may be explained by the ability of elite fast bowlers to find efficiency in maintaining stable ball velocity across bowling intensities despite the likelihood of subtle changes in bowling technique at lower bowling velocities.

Measures of roll and Player Load™ provided the strongest relationships with both prescribed intensity and ball velocity (Table 12). The gyroscope measure of roll represents the velocity of lateral trunk flexion. As opposed to yaw (thoracic rotation velocity), lateral trunk flexion velocity may be a more stable trait within the side-on, front-on or mixed bowling techniques used amongst fast bowlers. Both the peak resultant and peak Player Load™ variables rely on the tri-axial accelerometers housed within the wearable unit. The resultant accelerometer combines the raw outputs from all 3 accelerometer axes. Treating the raw accelerometer data with a filter may be required to improve the relationship between prescribed intensities and ball velocity.

It was not possible to obtain match-play data in this study, and consequently, we were unable to relate bowling intensity to a pre-determined maximum competition output. Further research is required to establish the validity and reliability of the microtechnology outputs during cricket match-play. Measuring bowling intensity may potentially provide a novel method of monitoring elite cricket fast bowlers. The paucity in literature around bowling intensity and injury outcome can largely be attributed to the difficulty in measuring fast bowling intensity. We propose that microtechnology outputs may provide a practical method of monitoring bowling intensity in fast bowlers.

A relationship between fast bowling workload and injury has been widely reported [21, 20, 47, 22]. More specifically, researchers have demonstrated increased injury risk with both under- and over-bowling [20] while others have shown a delayed effect of increased injury risk after bouts of increased acute bowling workload [47, 22, 21]. Previous researchers have studied the relationship between chronic (fitness) and acute (fatigue) bowling workloads and injury risk in cricket fast bowlers [21]. They identified that the injury likelihood of fast bowlers increased significantly in the week following a “spike” in acute workload relative to chronic workload [21]. Systematic increases in chronic bowling workloads decreased injury likelihood (10). Understanding the intensity of the bowling workload would help establish chronic bowling workloads relative to the match-play demands of the individual fast bowler. It is likely that in some cases, chronic workloads have been inflated with the inclusion of balls bowled at lower intensities, which may be misleading when identifying the preparedness of the bowler. Further research is required to explore if excluding lower intensity balls influences the acute:chronic workload ratio in fast bowlers.

Practically, there are many factors that play a role in prescribing bowling workloads to fast bowlers. These may include, but are not limited to; return from injury, competition restrictions, competition strategy, and playing conditions. To a degree, these factors can largely be controlled. However, there are other factors that are much more difficult to account for when preparing fast bowlers, including; the time between bowling innings in multi-day cricket and, the workload ‘flow-on’ effect amongst the bowlers within the team when one bowler sustains an injury in a competitive match. With this in mind, controlling bowling workloads prior to and after competition is vital in the preparation and management of fast bowlers from both a skill acquisition and injury prevention perspective. This integration of routinely used monitoring systems such as microtechnology to provide specific and meaningful data for

coaches, rehabilitation and strength and conditioning staff in cricket would provide both a novel and practical solution in monitoring bowling intensity.

6.6 Conclusions

In summary, we found a large to very large relationship between microtechnology outputs and both prescribed intensity and ball velocity. The large standard deviations at lower intensities can be explained by both the inability of the athlete to adhere to submaximal intensities and greater scope for variability at lower intensities. While further validation in varying competition and training settings is required, our findings demonstrate that microtechnology devices offer both a practical and adequate tool for prescribing and monitoring bowling intensity and workload in elite fast bowlers.

6.7 Practical Applications

Outputs from the microtechnology unit worn by cricket fast bowlers provide good insight into bowling intensity. This information provides a method of improved overall workload monitoring, particularly where varying bowling intensities are performed by the bowler. The use of wearable microtechnology to determine bowling intensity provides additional information to the routinely reported GPS profiles of cricket match-play and training [41]. Additionally, this data provides workload information for the coach from numerous players who may be competing or training in various locations at any one time that to date has been difficult to objectively quantify. Finally, implementing intensity into the current acute and chronic workload monitoring system may provide a clearer indication of the preparedness of the fast bowler to tolerate high workloads.

6.8 Acknowledgements

The authors would like to acknowledge the participants of the study. No financial assistance was provided for this study.

Chapter 7: Summary and Conclusions

7.1 Overview

This program of research investigated current methods of monitoring cricket fast bowling workload, using commercially available microtechnology to advance the current practices of workload analyses. The research first identified existing problems through rigorously reviewing the literature around workload monitoring for fast bowlers since the introduction of T20 cricket. In order to strengthen the understanding of workload experienced by cricket fast bowlers, observational evidence was also collected across both physical preparation and competition. The use of wearable technology was then explored, developing a reliable and valid measure to monitor workload in cricket fast bowlers.

Table 14. Summary of study outline, aims, and experimental hypotheses.

Chapter in Thesis	Study Outline	Aims	Experimental Hypotheses
Chapter 2	Systematic Review	1. Demonstrate the extent to which workload is related to injury and/or performance in elite cricket fast bowlers 2. Provide an update of the physical requirements of elite fast bowlers since the introduction of T20 cricket	(i) Limited scientific data on workload and fast bowling performance will be present since the introduction of T20 cricket

McNamara DJ, Gabbett TJ, Naughton G. Assessment of workload and its effects on performance and injury in elite cricket fast bowlers: a systematic review. *Sports Medicine*, 2016, DOI 10.1007/s40279-016-0588-8.

Chapter 3	Profile of competition and training demands in cricket	Profile and identify key fatigue and workload variables of cricket fast bowlers and non-fast bowlers	(ii) Training and competition demands of fast bowlers will be higher than non-fast bowlers
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McNamara DJ, Gabbett TJ, Naughton G, Farhart P, and Chapman P. Physical preparation and competition workloads and fatigue responses of elite junior cricket players. *International Journal of Sports Physiology and Performance*, 2013, 8 (5), 517-526.

Table 14. Continued.

Chapter 4	Validation of smart algorithms to detect fast bowling events	1. Validate the use of microtechnology devices in the automated detection of bowling events and counts 2. Refine the monitoring of bowling intensities	(iii) Wearable microtechnology will be both sensitive and specific in the detection of fast bowling events during training and match-play
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McNamara DJ, Gabbett TJ, Chapman P, Naughton G, and Farhart P. The validity of microsensors to automatically detect bowling events and counts in cricket fast bowlers. *International Journal of Sports Physiology and Performance*, 2015, 10 (1), 71-75.

Chapter 5	Variability of microtechnology in cricket fast bowlers	1. Document the variability of external workload measures between fast bowlers across bowling spells of varying duration	(iv) Outputs from wearable microtechnology will provide adequate reliability across repeated bowling events
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McNamara DJ, Gabbett TJ, Chapman P, Naughton G, and Farhart P. Variability of PlayerLoad™, Bowling Velocity and Performance Execution in Fast Bowlers Across Repeated Bowling Spells. *International Journal of Sports Physiology and Performance*, 2015, 10 (8), 1009-1014.

Chapter 6	Sensitivity of microtechnology to measure fast bowling intensity	1. Assess the relationship between prescribed bowling intensities, bowling velocity and data outputs from wearable microtechnology	(v) Wearable microtechnology will be sensitive to distinguish the intensity of a prescribed fast bowling event
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McNamara DJ, Gabbett TJ, Blanch P, and Kelly L. Relationship between wearable microtechnology device variables and cricket fast bowling intensity. 2016. *International Journal of Sports Physiology and Performance*, In review.

7.2 Summary of Major Findings

Table 14 summarises the study outline, aims, and experimental hypotheses. Expanding on this summary:

(i) *It was initially hypothesised that limited scientific data on workload and fast bowling performance would be available following the introduction of T20 cricket. A paucity of research with key variables examining fast bowling performance and the interaction with bowling workload was identified in the systematic review presented in Chapter 2. Although studies of fast bowling workload comprised a large proportion of published literature in elite cricket, the interaction of training and performance in competition over time was unstated. The review concluded that it remains difficult to objectively measure fast bowling performance. Available outcomes were limited to bowling velocity and execution during training settings. Performance during competition had not been explored. Thus, the results of the systematic review supported the hypothesis.*

(ii) *In Chapter 3, it was hypothesised that training and competition demands of fast bowlers was likely to be higher than non-fast bowlers. Using wearable GPS technology across physical preparation and competition in elite adolescent cricketers, this study showed that the external workload experienced by fast bowlers exceeded that of non-fast bowlers. Given that fast bowlers are required to bat and field in both competition and physical preparation, it is suggested that this difference in external workload is most likely attributed to the fast bowling events. The experimental hypothesis was strongly supported by the results of this study.*

(iii) *Chapter 4 addressed the hypothesis that wearable microtechnology would be both sensitive and specific in the detection of fast bowling events during training and match-play. Thus, the ability of wearable microtechnology to identify fast bowling events was explored. In*

both competition and training settings, algorithms using the interaction between the GPS, accelerometers and gyroscopes housed in the wearable sensors were able to detect fast bowling events. Sensitivity of detection was 99.5% in competition and 99.0% in training. The specificity of detecting fast bowling events was 74.0% in competition and 98.1% in training. Thus, this hypothesis was also strongly supported by the results of the study.

(iv) *Chapter 5 explored whether outputs from wearable microtechnology would provide adequate reliability across repeated bowling events.* Player Load™ demonstrated adequate stability over repeated bowling spells. In comparison, measures of bowling performance varied to a greater extent. Bowling velocity measures exhibited low CV% whilst bowling execution had a CV% in excess of 20%. It is concluded that the hypothesis was only partially supported and was again dependent on specific capacities within the technology.

(v) *The final hypothesis in Chapter 6 was that wearable microtechnology would have the sensitivity to identify the intensity of a prescribed fast bowling event.* During a range of prescribed bowling intensities, relative measures of Player Load™ and gyroscope roll outputs had very large relationships with prescribed bowling intensities and relative bowling velocity. Thus, the hypothesis was supported; wearable microtechnology provided the ability to indicate the intensity of fast bowling events.

7.3 Points of Difference

This program of research advances the existing understanding of fast bowling workload, and provides practical outcomes for measuring fast bowling workload and performance.

The points of difference made by this program of research are:

(i) The designed research program strengthened the level of evidence around the need to monitor workload in fast bowling cricketers. The systematic review presented in this thesis identified that fast bowling workload is a key contributor to injury likelihood, which is further complicated by the introduction of T20 cricket. Typical field-based practice in monitoring fast bowling workload is a simple bowling count. Although this provides an indication of a fast bowler's preparation or readiness to compete or practice, it fails to account for the potential variation of bowling intensities across the accumulated load. The systematic review additionally explored the interaction between workload and performance in situ, extending beyond previous reviews which have only examined workload and injury.

(ii) This thesis was the first to combine (1) the external workload demands of cricket training and competition, (2) biomarkers of physiological stress, (3) subjective markers of perceived fatigue, and (4) measures of neuromuscular function to advance the understanding of the dose-response relationship of cricket workload in fast bowlers and non-fast bowlers. Because not all markers responded in the same way in fast bowlers, it was concluded that multiple markers may provide a stronger workload profile and that individualised monitoring strategies are required.

(iii) Current methodologies of fast bowling workload monitoring may mask or lack the sensitivity to understand individual responses and rates of response over short and longer term periods. This program of research examined the interaction of wearable technologies and fast

bowling load with the aim to provide diversity in current workload monitoring practices, while doing so via practical means. Exciting possibilities for microtechnology were identified, with a strong capacity to detect individual differences and variations in workloads.

7.4 Strengths

The strengths of this program of research are summarised as:

- (i)* Advancing current knowledge of how to better manage a high risk playing group.
- (ii)* Investigating a representative population of elite athletes within this sport.
- (iii)* Validating an innovative algorithm for a cricket related action. Overall, this thesis identified the validity, reliability and sensitivity of the action-specific demands on cricket fast bowlers.

7.5 Limitations

Sample sizes in research involving elite athletes such as fast bowling cricketers will always appear small. Although recruitment involved relatively small samples of elite cricketers, this sample size represents upwards of 90% of all possible players available for recruitment. For example, the 26 elite cricketers profiled in Chapter 4 represented the entire state pathways program. Therefore, while sample sizes remain somewhat small they should be interpreted as highly representative.

A further limitation may lie in the external validity of the results; with relevance mainly to elite junior and elite national and international players bowling under Australian conditions. However, with the “proof of concept” supporting the use of microtechnology in this program

of research, there is now scope to expand internationally. National cricketing bodies such as Cricket Australia have invested in a pooled collection of microtechnology devices and cloud-based storage to better capture and share data on workload management of developing and high profile fast bowlers.

7.6 Future Directions

The advancements in fast bowler workload management presented in this thesis have provided opportunity to explore the interaction between wearable technologies and athlete workload monitoring. More specifically the future directions for applied researchers are:

(i) New thinking for defining acute and chronic workloads through direct measures of task-specific intensities (Figure 13). The measure of task-specific intensity in sport will provide context around how both acute and chronic loads are accumulated and provide feedback regarding the planned and actual workloads experienced by athletes (for more information please refer to Appendix B).

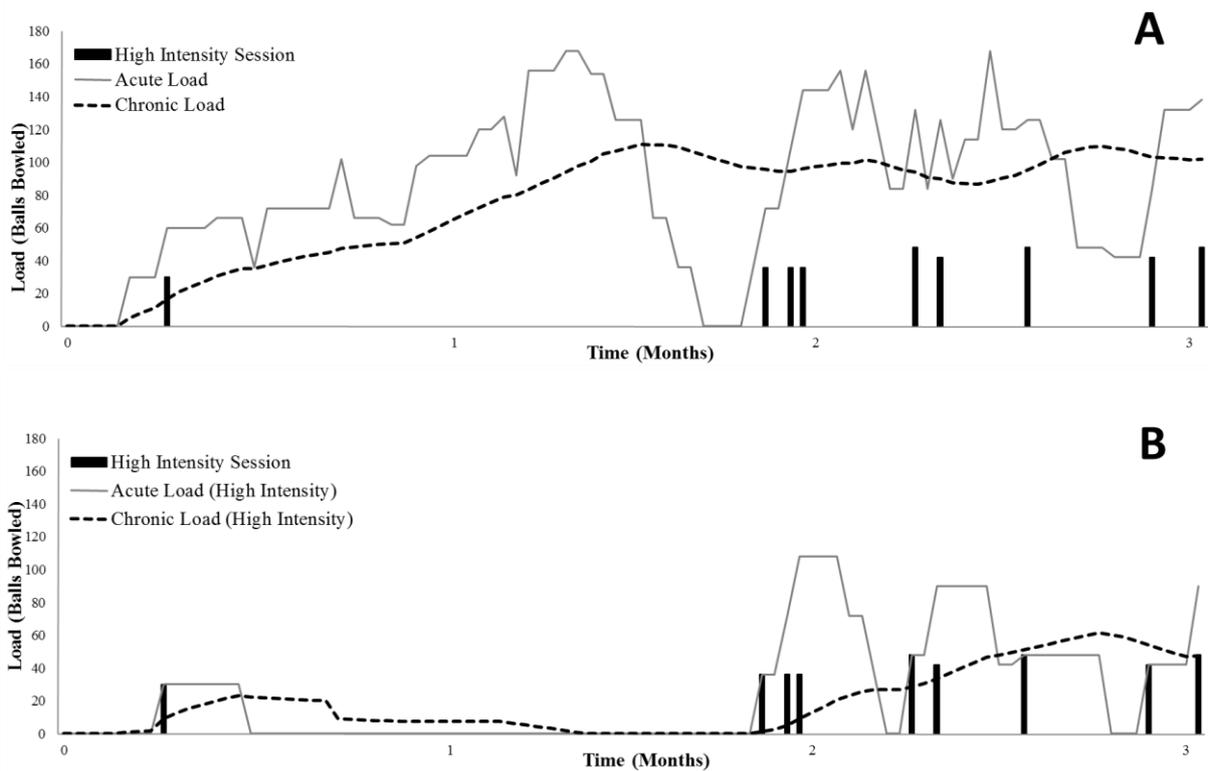


Figure 13. Acute and chronic bowling loads of an individual fast bowler over 3 months of a cricket preseason. Acute Load = 7-day average. Chronic Load = 28-day average. (A) All balls bowled included. (B) Only balls bowled at high intensity included. Balls bowled at high intensity were defined as a ball bowled at greater than 80% of the highest Player Load™ score recorded [50].

(ii) While the fast bowling intensity variables presented in this thesis require a level of post-collection processing, the capacity of new technology and processing power within wearable technologies will provide the opportunities to deliver immediate feedback to athletes and coaching staff.

(iii) The wearable technologies used in this thesis have the ability to interact with other technologies including video and heart rate. Further interaction with other technologies will provide scope for advancements in machine learning and potentially greater accuracy and specificity in load monitoring of individual athletes.

(iv) Using accessible technologies such as smart phones provides opportunity for researchers, athletes and coaches to measure and record workload. With the development of applications, the hardware within technologies such as smart phones may be capable of detecting and recording cricket-specific events on a basic level. Development of such applications provide opportunity for greater scope of player management across community programs.

(v) Wearable technology is now also used by sporting broadcasters to provide in-depth content for viewers. At present, this information is limited to running distance and velocity. The use of smart algorithms and wearable technologies in cricket will enable greater engagement and understanding of the workloads experienced by elite fast bowlers for the cricket supporter.

(vi) Collection of external workloads and cricket-specific events via wearable technology is advancing the ability to pool data of numerous teams and players across cricket competitions and seasons. The vastness of this data allows for greater depth of analysis in performance, load and injury.

7.7 Practical Applications

The findings presented in this thesis have significant impact on the current load monitoring practices in cricket. The use of wearable technology is common in team sport. The findings of this thesis advance the use of these technologies beyond simple observations of routinely used GPS variables. Accessing data from the accelerometers, gyroscopes and magnetometers housed within the GPS device provides greater potential for quantifying the loads experienced by cricketers and specifically fast bowlers. These data are capable of being integrated and

presented in commonly used athlete monitoring systems, allowing greater accessibility for coaches and support staff.

The manner in which bowling workloads are measured has been influenced by the findings of this thesis. Until now, the influence of bowling intensity on an individual's acute and chronic bowling loads has been difficult to objectively and individually quantify. It is highly likely that bowling intensity will influence preparedness of a fast bowler. Chapter 6 presents the first attempt to practically quantify fast bowling intensity in training and match environments using wearable microtechnology.

Routinely worn wearable technology in young fast bowlers will provide better understanding of the significance of career bowling load on injury likelihood. While career workload has been shown to influence injury likelihood in elite fast bowlers [48], combining measures of bowling load and intensity with technique and physical maturation changes, provides the greatest scope for understanding injury likelihood and performance in fast bowlers.

7.8 Conclusions

This thesis advances the management and monitoring of cricket fast bowlers. Cricket match-play demands have changed over the past 10 years and wearable microtechnology appears to be a viable tool in the monitoring of cricket fast bowlers. In addition, microtechnology provides the ability to challenge the current methods of workload management in cricket fast bowlers.

This thesis supports previous literature identifying that cricket fast bowlers' experience greater external load than other player types. Furthermore, the act of fast bowling is directly linked to increased likelihood of injury. Workload history has been identified as a contributing factor to injury likelihood and type. The technology identified in this thesis advances the workload monitoring of cricket fast bowlers which is crucial to proactive planning in elite adolescent and adult fast bowlers.

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Appendices

Appendix A - Evidence of Publications

Chapter 2 – McNamara DJ, Gabbett TJ, Naughton G. Assessment of workload and its effects on performance and injury in elite cricket fast bowlers. *Sports Medicine*, 2016, DOI 10.1007/s40279-016-0588-8.

Sports Med
DOI 10.1007/s40279-016-0588-8



SYSTEMATIC REVIEW

Assessment of Workload and its Effects on Performance and Injury in Elite Cricket Fast Bowlers

Dean J. McNamara¹ · Tim J. Gabbett^{1,2} · Geraldine Naughton³

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Abstract

Background Cricket is distinctly positioned in the world of elite sports because three different formats now exist, each with characteristically different workload requirements. Fast bowlers have greater match-play workload requirements and are at greater injury risk than other positions. An update on the current cricket literature regarding fast bowling match-play physiology, workload, and injury is required to demonstrate the extent to which workload is related to performance and injury in elite fast bowlers since the introduction of 20-over cricket in 2005.

Methods The current review examined articles published in English with data collected from 2005 onwards pertaining to in situ cricket fast bowling physiology, match play, injury, and workload. Four databases were searched using the combinations of the following keywords: 'cricket' and 'bowl', inclusive of 'pace', 'fast', 'medium', or 'seam' bowling. Articles from 2005 onwards with male participants, high-performing or elite, and fast bowlers in the game of cricket were considered for inclusion. Only workload assessments captured in a field setting were included.

Results A total of 751 articles were identified. Exclusions included 527 duplicates, papers pre-2005, review articles, and abstracts. A further 185 articles were excluded after review of titles and abstracts that were deemed to be outside the scope of

research or population. The full texts of 39 articles were reviewed, with only 17 included in this systematic review. In five articles reviewed, fast bowlers had a greater workload than other player types. Bowling workload history was reviewed in seven articles and appeared to have a complex interaction with likelihood of injury and injury type.

Conclusion Fast bowling workload has a well recognised relationship with injury and performance. Although monitoring acute and chronic workloads of fast bowlers remains the most ideal method for identifying preparedness and injury likelihood in fast bowlers, complexities exist that make the systematic prescription of bowling workloads difficult. Advances in technology to monitor workloads may provide further insight into the intensity and workloads of fast bowlers.

PROSPERO registration number: CRD42015032466

Key Points

Although elite fast bowlers are generally adequately prepared for the acute workloads required for cricket match play, large 'spikes' in acute workloads can manifest as delayed injury risk.

Twenty20 cricket complicates workload monitoring, injury management, and physical preparation in cricket.

Interaction between advances in athlete tracking systems and longitudinal injury research is required to advance the understanding of fast bowling management.

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Published online: 19 July 2016

Springer

Chapter 3 - McNamara DJ, Gabbett TJ, Naughton G, Farhart P, and Chapman P. Physical preparation and competition workloads and fatigue responses of elite junior cricket players. *International Journal Sports Physiology Performance*, 2013, 8 (5), 517-526.

International Journal of Sports Physiology and Performance, 2013, 8, 517-526
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INTERNATIONAL JOURNAL OF
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ORIGINAL INVESTIGATION

Training and Competition Workloads and Fatigue Responses of Elite Junior Cricket Players

Dean J. McNamara, Tim J. Gabbett, Geraldine Naughton,
Patrick Farhart, and Paul Chapman

Purpose: This study investigated key fatigue and workload variables of cricket fast bowlers and nonfast bowlers during a 7-wk physical-preparation period and 10-d intensified competition period. **Methods:** Twenty-six elite junior cricketers (mean \pm SD age 17.7 ± 1.1 y) were classified as fast bowlers ($n = 9$) or nonfast bowlers ($n = 17$). Individual workloads were measured via global positioning system technology, and neuromuscular function (countermovement jump [relative power and flight time]), endocrine (salivary testosterone and cortisol concentrations), and perceptual well-being (soreness, mood, stress, sleep quality, and fatigue) markers were recorded. **Results:** Fast bowlers performed greater competition total distance (median [interquartile range] 7049 [3962] m vs 5062 [3694] m), including greater distances at low and high speeds, and more accelerations (40 [32] vs 19 [21]) and had a higher player load (912 [481] arbitrary units vs 697 [424] arbitrary units) than nonfast bowlers. Cortisol concentrations were higher in the physical-preparation (mean \pm 90% confidence intervals, % likelihood; $d = -0.88 \pm 0.39$, 100%) and competition phases ($d = -0.39 \pm 0.30$, 85%), and testosterone concentrations, lower ($d = 0.56 \pm 0.29$, 98%), in the competition phase in fast bowlers. Perceptual well-being was poorer in nonfast bowlers during competition only ($d = 0.36 \pm 0.22$, 88%). Differences in neuromuscular function between groups were unclear during physical preparation and competition. **Conclusions:** These findings demonstrate differences in the physical demands of cricket fast bowlers and nonfast bowlers and suggest that these external workloads differentially affect the neuromuscular, endocrine, and perceptual fatigue responses of these players.

Keywords: fast bowling, GPS, well-being, neuromuscular, endocrine

Cricket is a popular team sport, played predominantly in Commonwealth countries. It is played by two teams of 11 players each, and specific roles of players can be classified into various subgroups including batsmen, fast bowlers, spin bowlers, and wicket keepers. Finer classifications within these subgroups can also be identified. While each player has specific roles on a team, all players are required to field throughout the course of a game. Variations in game formats include multiday, 50-over, and 20-over cricket. Differences between formats are identified in the length of each match, with multiday cricket lasting up to 5 consecutive days and 50-over and 20-over matches completed in approximately 8 and 4 hours, respectively.

Time-motion analysis has been used to describe the physical demands of cricket batting and fielding.¹ Global

positioning system (GPS) technology has contributed to an understanding of the differences in match load and intensities between 1-day and multiday cricket formats. Petersen et al² identified differences in match intensity between fast bowlers and nonfast bowlers; fast bowlers covered more distance and at greater intensities than nonfast bowlers. In the same study it was found that game format also influenced the load and intensity of fast bowlers and nonfast bowlers, with 20-over matches resulting in higher average intensities than 50-over and multiday cricket. Previous research has found that while 1-day cricket formats had greater intensities, multiday cricket involved greater overall load.³ The activity profiles of competitive match play and cricket training activities typically used to develop skill and physical fitness have also been investigated.⁴ Petersen et al⁴ found higher heart rate and blood lactate concentration during conditioning training than competition. Few other studies have investigated the physical demands of cricket, with the majority of them limited to the acute responses to cricket-related tasks reporting heart rate, blood lactate concentration, and hydration status in bowling spells.^{5,6} Duffield et al⁷ investigated both physiological and performance responses to repeated spells of fast bowling; 6-over spells of fast bowling resulted in increases in rating of

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Chapter 4 - McNamara DJ, Gabbett TJ, Chapman P, Naughton G, and Farhart P. The validity of microensors to automatically detect bowling events and counts in cricket fast bowlers. *International Journal Sports Physiology Performance*, 2015, 10 (1), 71-75.

International Journal of Sports Physiology and Performance, 2015, 10, 71-75
<http://dx.doi.org/10.1123/ijssp.2014-0062>
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ORIGINAL INVESTIGATION

The Validity of Microsensors to Automatically Detect Bowling Events and Counts in Cricket Fast Bowlers

Dean J. McNamara, Tim J. Gabbett, Paul Chapman, Geraldine Naughton, and Patrick Farhart

Purpose: Bowling workload is linked to injury risk in cricket fast bowlers. This study investigated the validity of microtechnology in the automated detection of bowling counts and events, including run-up distance and velocity, in cricket fast bowlers. **Method:** Twelve highly skilled fast bowlers (mean \pm SD age 23.5 ± 3.7 y) performed a series of bowling, throwing, and fielding activities in an outdoor environment during training and competition while wearing a microtechnology unit (MinimaxX). Sensitivity and specificity of a bowling-detection algorithm were determined by comparing the outputs from the device with manually recorded bowling counts. Run-up distance and run-up velocity were measured and compared with microtechnology outputs. **Results:** No significant differences were observed between direct measures of bowling and nonbowling events and true positive and true negative events recorded by the MinimaxX unit ($P = .34$, $r = .99$). The bowling-detection algorithm was shown to be sensitive in both training (99.0%) and competition (99.5%). Specificity was 98.1% during training and 74.0% during competition. Run-up distance was accurately recorded by the unit, with a percentage bias of 0.8% ($r = .90$). The final 10-m (-8.9% , $r = .88$) and 5-m (-7.3% , $r = .90$) run-up velocities were less accurate. **Conclusions:** The bowling-detection algorithm from the MinimaxX device is sensitive to detect bowling counts in both cricket training and competition. Although specificity is high during training, the number of false positive events increased during competition. Additional bowling workload measures require further development.

Keywords: workload, GPS, team sport, training, competition

Cricket is a popular team sport, played predominantly in Commonwealth countries. The sport comprises 2 teams of 11 players; specific roles of players can be classified into various subgroups including batsmen, fast bowlers, spin bowlers, and wicket keepers. Fast bowlers usually account for 3 to 5 of the 11 players on each team. Competition bowling workloads depend on both match type and the match-play strategy adopted by the team captain, while training workloads reflect the volume, intensity, and frequency prescribed by team coaches and support staff.

Fast bowlers have greater physical workloads and higher injury rates than other player types.^{1,2} To date, fast-bowling workload monitoring has been limited to the number of balls bowled. When self-reported accurately, this is a cost-effective and practical method of monitoring bowling workload for large groups of athletes. However, there is the potential for inaccuracies in athlete self-reporting, particularly during training. In elite cricket, where fast-bowling workloads have been attributed to injury likelihood, accurate measures of workload are vital in the management of fast bowlers.

With the assumption that not every ball bowled during training is representative of competition intensity, the simple method of reporting all balls bowled becomes a relatively broad definition of bowling workload. Ball speed is attributed to various parts of the bowling action, including the run-up speed.³ Modification of

bowling action may influence the delivery speed and bowling performance, as well as the total load experienced by the bowler during that event. Bowling workload monitoring has also been identified as vital in both injury prevention and physical conditioning.¹ Given the demanding nature of fast bowling, and the high risk of injury, efficient and accurate measures of bowling events are vital in understanding the workloads of fast bowlers and the fatigue associated with this activity.

Global positioning system (GPS) technology has been shown to provide a valid measure of acceleration, velocity, and total distance.^{4,5} This technology has contributed to an understanding of the differences in match load and intensities between 1-day and multiday cricket formats.^{6,7} With the addition of accelerometer and gyroscope technologies, these microtechnology units have become a powerful tool in monitoring athlete workloads. Indeed, manufacturers of microtechnology units have designed specific algorithms that have been used in other team sports to automatically identify important match and training events.⁷ Researchers in collision sports have previously validated the automated quantification of tackles using microtechnology units.^{8,9} However, the accuracy of this system in fast bowling is yet to be validated. The significance of such a tool for fast-bowling workload monitoring is twofold. First, it may improve the accuracy and ease in identification of important competition events, and second, it may allow for greater accuracy and easier interpretation of segmented and total bowling workloads during training.

With this in mind, the primary aim of this study was to validate the use of microtechnology devices in the automated detection of bowling events and counts in cricket fast bowlers during training and competition against current monitoring methods. A secondary aim of this study was to further refine the monitoring of bowling

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Chapter 5 - McNamara DJ, Gabbett TJ, Chapman P, Naughton G, and Farhart P. Variability of PlayerLoad™, bowling velocity and performance execution in fast bowlers across repeated bowling spells. *International Journal Sports Physiology Performance*, 2015, 10 (8), 1009-1014.

International Journal of Sports Physiology and Performance, 2015, 10, 1009-1014
<http://dx.doi.org/10.1123/ijsp.2014-0497>
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ORIGINAL INVESTIGATION

Variability of PlayerLoad, Bowling Velocity, and Performance Execution in Fast Bowlers Across Repeated Bowling Spells

Dean J. McNamara, Tim J. Gabbett, Paul Chapman, Geraldine Naughton, and Patrick Farhart

Purpose: The use of wearable microtechnology to monitor the external load of fast bowling is challenged by the inherent variability of bowling techniques between bowlers. This study assessed the between-bowlers variability in PlayerLoad, bowling velocity, and performance execution across repeated bowling spells. **Methods:** Seven national-level fast bowlers completed two 6-over bowling spells at a batter during a competitive training session. Key dependent variables were PlayerLoad calculated with a MinimaxX microtechnology unit, ball velocity, and bowling execution based on a predetermined bowling strategy for each ball bowled. The between-bowlers coefficient of variation (CV), repeated-measures ANOVA, and smallest worthwhile change were calculated over the 2 repeated 6-over bowling spells and explored across 12-over, 6-over, and 3-over bowling segments. **Results:** From the sum of 6 consecutive balls, the between-bowlers CV for relative peak PlayerLoad was 1.2% over the 12-over bowling spell ($P = .15$). During this 12-over period, bowling-execution ($P = .43$) scores and ball-velocity ($P = .31$) CVs were calculated as 46.0% and 0.4%, respectively. **Conclusions:** PlayerLoad was found to be stable across the repeated bowling spells in the fast-bowling cohort. Measures of variability and change across the repeated bowling spells were consistent with the performance measure of ball velocity. The stability of PlayerLoad improved when assessed relative to the individual's peak PlayerLoad. Only bowling-execution measures were found to have high variability across the repeated bowling spells. PlayerLoad provides a stable measure of external workload between fast bowlers.

Keywords: workload, microsensors, team sport, training

Cricket is a popular team sport that is played internationally. Cricket teams competing at elite levels consist of various player types that specialize in their positions. Fast bowlers make up one of these specialist positions and have been identified as having greater physical workloads than other player types.^{1,2} The increasing variations in game formats now include multiday 50-over and 20-over cricket. Highly skilled fast bowlers in all game formats are characterized by having both greater sustainability in bowling velocity and greater accuracy than less-skilled fast bowlers.³ Bowling velocity and accuracy are routinely reported as performance measures in the fast-bowling literature.^{3,4} While there are rules and regulations that to an extent normalize the bowling action in cricket, there is inherent variability in fast-bowling technique.⁵ Commonly, fast bowlers compete across all game formats, despite the large disparities in acute and chronic workload requirements in both training and competition.¹ With the inherent variability in bowling technique between fast bowlers and the workload resulting from competition type, measures of fast-bowling performance and, more important, external workload need to remain stable across both shorter and longer bowling spells.

Previous research has identified the physiological characteristics of fast-bowling spells.⁶ Two 6-over spells of fast bowling have been shown to increase rating of perceived exertion (peaking at 6.5

± 0.8 arbitrary units) and blood lactate concentrations (from 1.5 ± 0.3 to 5.0 ± 1.5 mmol/L) and reduce blood glucose concentrations (from 6.3 ± 0.7 to 5.4 ± 0.4 mmol/L).⁶ Variability in bowling accuracy was also monitored throughout the repeated bowling spells; coefficients of variation (CV) for bowling accuracy of 39% for spell 1 and 43% for spell 2 were reported. The protocol scored the accuracy of balls bowled relative to a predetermined target.³ Despite showing that fast bowling is physically demanding, the influence of bowling duration and possibly fatigue on between-overs bowling accuracy and velocity remains unclear. Other studies have investigated bowling accuracy and velocity in elite and junior elite fast bowlers and reported an uncoupling of ball velocity and accuracy among elite fast bowlers.³ This nonlinear relationship between ball velocity and accuracy suggests that these variables should be analyzed independently.

Fast-bowling performance is largely influenced by environmental conditions. The nature of the pitch conditions, wind, and even the country in which the match is played can influence the tactical decision making of the fast bowler and therefore may change the skill-execution requirements.⁷ Previous research has found that fast bowlers have greater levels of both accuracy and consistency when bowling at "good" lengths than when bowling at "full" lengths.³ This suggests that functional accuracy or bowling execution in cricket is more important than simply bowling at a set target with no batter, particularly as bowling targets and bowling lengths are influenced greatly by match-play strategy for individual batters and pitch conditions.⁷ Measures of fast-bowling performance need to be robust enough to account for the varying requirements of competition type and also be stable enough to account for changes in performance.

Bowling workload has been identified as a contributor to injury likelihood.⁸ To date, workload monitoring has been limited to counting the number of balls bowled by fast bowlers during both

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Appendix B – Published Editorial

McNamara DJ, Gabbett TJ, Naughton G, Orchard J. How submarine and guided missile technology can help reduce injury and improve performance in cricket fast bowlers. *British Journal of Sports Medicine*. 2016. doi:10.1136/bjsports-2015-095935

Downloaded from <http://bjsm.bmj.com/> on March 27, 2016 - Published by group.bmj.com

BJSM Online First, published on March 25, 2016 as 10.1136/bjsports-2015-095935

Editorial

How submarine and guided missile technology can help reduce injury and improve performance in cricket fast bowlers

Dean J McNamara,¹ Tim J Gabbett,^{1,2} Geraldine Naughton,³ John W Orchard⁴

CRICKET—TRADITION MEETS FLARE

There are three formats of cricket competition (multiday unlimited overs with approximately 150–300 overs delivered by one team, 50-over and Twenty20; T20—20 overs). An over is a measure of workload—6 consecutive deliveries by a bowler. A delivery carries the ball to the batsman 20 m away at speeds varying from 80 to 160 km/h.

In these three forms of cricket, a bowler's workload may vary from 60 to 4 overs in one of the matches. Because of this varying workload and intensity, cricket match-play provides a complex challenge for clinicians and coaches.¹ Arguably, no other professional sport has experienced greater changes in competitive workload demands than cricket over the past 10 years; perhaps most specifically via the introduction of T20 cricket.

FAST BOWLING—A SPORTING ACTIVITY PUNCTUATED WITH INJURY RISK

Fast bowlers are at greater risk of injury than their team mates,² and the nature of the injuries sustained tend to involve extensive rehabilitation periods. These injuries are largely associated with repetitive large forces experienced by fast bowlers during their bowling actions resulting in accumulated stresses.³ With a predominance of trunk and lower limb injury in fast bowlers, the injury profile is more similar to a football player than a baseball pitcher; the latter sustaining mainly shoulder and elbow injuries.⁴

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ACUTE:CHRONIC BOWLING WORKLOADS—TRAINING FOR THE MARATHON AND THE SPRINT

Acute bowling workloads represent a 7-day average and chronic bowling workloads a 28-day rolling average.⁵ In the pre-T20 era both bowling too much and too little were linked with increased injury risk.⁶ Recent analysis has identified that the rate of increase in bowling workload (represented by the acute:chronic workload ratio) is more reflective of injury risk than the absolute amount of bowling.⁷

Over the past 10 years, the end goal could be a 3 h cricket match, a 5-day cricket match, or routinely, both. Progressing a bowler to a window of decreased injury likelihood requires workload to be viewed as a moving target. Different bowling workloads are required to prepare a player to bowl 4 overs (as in the case of a T20 match) or upwards of 50 overs (as in the case of a multiday match). When preparing fast bowlers for concurrent multiday cricket and shorter forms of the game, it is possible that a fast bowler may be best prepared for the largest workload demand which is most likely associated with the bowling load of multiday cricket.

TRACKING THE MISSILE—USING TECHNOLOGY TO MONITOR BOWLING WORKLOAD

Currently, the reporting of bowling loads requires players and coaches to manually record the number of deliveries bowled during each training session. However, a potential flaw exists within the current model of acute:chronic workload monitoring of fast bowlers. An assumption exists that all balls bowled are equal. Counting all deliveries, including those that are performed at submaximal intensities, may not accurately reflect the bowler's preparedness to perform at maximal intensities. Recently, advances in wearable microtechnology have resulted in 'smart algorithms' to automatically

count balls delivered by fast bowlers.⁸ These 'smart algorithms' rely on the interaction of the accelerometers, magnetometers and gyroscopes housed within the wearable unit; the same technology used to navigate submarines, guided missiles and spacecraft. Once the technology detects a ball bowled by the fast bowler, measures of bowling intensity can be attached to that individual delivery via the accelerometer and gyroscope outputs. Tagging individual balls with an intensity measure provides both immediate analysis such as identifying effort balls, or potentially a drop in performance due to fatigue, or longer term workload analysis in establishing inclusion and exclusion criteria for the make-up of the acute:chronic workload ratio.

These microtechnology devices offer a stable measure of bowling 'load' across repeated bowling spells. In addition, this microtechnology may quantify the intensity of individual deliveries bowled in both training and competition. Measuring bowling intensity for individual balls or sessions provides context for the acute and chronic workload of the individual bowler, and ultimately the preparedness of the bowler for the maximal workload of the immediate competition. Automated measures of bowling workload and intensity provide opportunity to enhance the monitoring of fast bowling preparation for both injury prevention and performance outcomes (figure 1).

LONGITUDINAL INJURY RESEARCH, IMPLEMENTING NEW TECHNOLOGIES AND CHALLENGES

Advances in microtechnology have allowed some insight into the workloads of different cricket match-play formats,¹ and the training used to prepare for these competitions.⁸ We expect wearable technology will become routine in cricket over the next decade. This will be driven from both the perspective of athlete well-being and performance, concomitantly supporting the need for novel metrics of player performance in broadcasting to sporting fans. Customised metrics from this technology that are unique to cricket will advance the understanding of fast bowling preparedness, optimising workload monitoring and assist in injury prevention strategies for fast bowlers.

Contributors DJM, TJG, GN and JWO all contributed equally to the writing of the editorial. DJM and TJG developed the article concept.

Competing interests None declared.

**How submarine and guided missile technology can help reduce injury and improve performance
in Cricket Fast Bowlers**

This editorial has been accepted for publication following peer review. Full reference details are:

McNamara DJ, Gabbett TJ, Naughton G, Orchard J. How submarine and guided missile technology can help reduce injury and improve performance in cricket fast bowlers. *British Journal of Sports Medicine*. 2016. doi:10.1136/bjsports-2015-095935

Cricket – Tradition Meets Flare

There are three formats of cricket competition (multi-day unlimited overs with approximately 150-300 overs delivered by one team), 50-over, and Twenty20; T20 – 20 overs). An over is a measure of workload – 6 consecutive deliveries by a bowler. A delivery carries the ball to the batsman 20 meters away at speeds varying from 80-160 km/hr.

In these three forms of cricket a bowler's workload may vary from 60 overs to 4 overs in one of the matches. Because of this varying workload and intensity, cricket match-play provides a complex challenge for clinicians and coaches [41]. Arguably, no other professional sport has experienced greater changes in competitive workload demands than cricket over the past 10 years; perhaps most specifically via the introduction of T20 cricket.

Fast Bowling – A Sporting Activity Punctuated with Injury Risk

Fast bowlers are at greater risk of injury than their team mates [82], and the nature of the injuries sustained tend to involve extensive rehabilitation periods. These injuries are largely associated with repetitive large forces experienced by fast bowlers during their bowling actions resulting in accumulated stresses [47]. With a predominance of trunk and lower limb injury in fast bowlers, the injury profile is more similar to a football player than a baseball pitcher; the latter sustaining mainly shoulder and elbow injuries [83].

Acute:Chronic Bowling Workloads – Training for the Marathon and the Sprint

Acute bowling workloads represent a 7-day average and chronic bowling workloads a 28-day rolling average [84]. In the pre-T20 era both bowling too much and too little were linked with increased injury

risk [19]. Recent analysis has identified that the rate of increase in bowling workload (represented by the acute:chronic workload ratio) is more reflective of injury risk than the absolute amount of bowling [20].

Over the past 10 years, the end goal could be a 3-hour cricket match, a 5-day cricket match, or routinely, both. Progressing a bowler to a window of decreased injury likelihood requires workload to be viewed as a moving target. Different bowling workloads are required to prepare a player to bowl 4 overs (as in the case of a T20 match) or upwards of 50 overs (as in the case of a multi-day match). When preparing fast bowlers for concurrent multi-day cricket and shorter forms of the game, it is possible that a fast bowler may be best prepared for the largest workload demand which is most likely associated with the bowling load of multi-day cricket.

Tracking the Missile - Using Technology to Monitor Bowling Workload

Currently, the reporting of bowling loads requires players and coaches to *manually record* the number of deliveries bowled during each training session. However, a potential flaw exists within the current model of acute:chronic workload monitoring of fast bowlers. An assumption exists that all balls bowled are equal. Counting all deliveries including those that are performed at sub-maximal intensities, may not accurately reflect the bowler's preparedness to perform at maximal intensities. Recently, advances in wearable microtechnology have resulted in 'smart algorithms' to automatically count balls delivered by fast bowlers [45]. These 'smart algorithms' rely on the interaction of the accelerometers, magnetometers and gyroscopes housed within the wearable unit; the same technology used to navigate submarines, guided missiles, and spacecraft. Once the technology detects a ball bowled by the fast bowler, measures of bowling intensity can be attached to that individual delivery via the accelerometer and gyroscope outputs. Tagging individual balls with an intensity measure provides both immediate

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These microtechnology devices offer a stable measure of bowling 'load' across repeated bowling spells. In addition, this microtechnology may *quantify the intensity* of individual deliveries bowled in both training and competition. Measuring bowling intensity for individual balls or sessions provides context for the acute and chronic workload of the individual bowler, and ultimately the preparedness of the bowler for the maximal workload of the immediate competition. Automated measures of bowling workload *and* intensity provide opportunity to enhance the monitoring of fast bowling preparation for both injury prevention and performance outcomes (Figure 13).

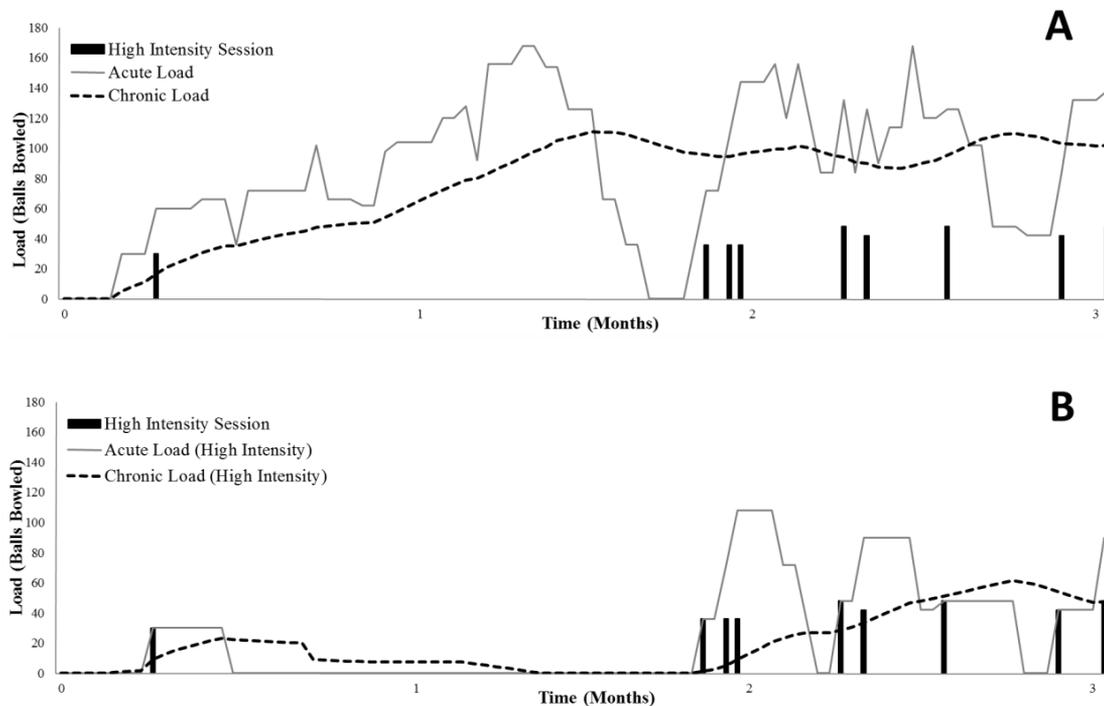


Figure 13. Acute and chronic bowling loads of an individual fast bowler over 3 months of a cricket preseason. Acute Load = 7-day average. Chronic Load = 28-day average. (A) All balls bowled included. (B) Only balls bowled at high intensity included. Balls bowled at high intensity were defined as a ball bowled at greater than 80% of the highest Player Load™ score recorded.

Longitudinal Injury Research, Implementing New Technologies and Challenges

Advances in microtechnology have allowed some insight into the workloads of different cricket match-play formats [41], and the training used to prepare for these competitions [45]. We expect wearable technology will become routine in cricket over the next decade. This will be driven from both the perspective of athlete wellbeing and performance; concomitantly supporting the need for novel metrics of player performance in broadcasting to sporting fans. Customised metrics from this technology that are unique to cricket will advance the understanding of fast bowling preparedness, optimising workload monitoring and assist in injury prevention strategies for fast bowlers.

Appendix C - Information Letters and Consent Forms

Chapter 3. Physical preparation and competition workloads and fatigue responses of elite junior cricket players

INFORMATION LETTER TO PARTICIPANTS

TITLE OF PROJECT: Physical preparation and competition workloads and fatigue responses of elite junior cricket players
.....

PRINCIPAL INVESTIGATOR: Dr Tim Gabbett.....

STUDENT RESEARCHER : Mr Dean McNamara

PROGRAMME IN WHICH ENROLLED: ...Ph.D.....

Dear Participant,

You are invited to participate in a research project designed for athletes competing in the age national cricket championships during the 2011/12 cricket season. The purpose of this study is to monitor the workloads of adolescent cricketers during preparation and competition. The researchers will be collecting data regarding neuromuscular, endocrine, and perceptual markers of fatigue. This will be done through various counter movement jumps (CMJ), saliva assays, and questionnaires. Workload and performance variables will be taken throughout the study involving video and GPS analysis. This research is for a PhD project and will lead to a thesis.

The study will have minimal inconvenience on your preparation with much of the data already a part of the normal screening procedures undertaken by your state organisation. Testing will occur at scheduled training and during the national cricket championships. Questionnaires will be completed at a time that best fits in with the participant. If any participant suffers physical injury or psychological stress during the duration of this project they will be directed to the preferred and relevant services providers of Cricket NSW.

As a participant you will be asked to complete various CMJ's, preparing saliva samples for analysis, and daily subjective measures of fatigue. Video analysis will also take place during the competition phase of the data collection. You will be asked if you are willing to wear a GPS unit throughout training and competition. The GPS units are small matchbox sized units worn in a foam pouch between your shoulder blades. All data and samples will be stored on the university, in Strathfield.

Benefits from participation include enhanced self-awareness of overreaching/overtraining and comprehensive workload analysis. Risk to any participant is minimal as no athlete will be asked to do more than their current training and match workload set out by the current coaches.

It is possible that you will be asked to attend training sessions up to 30min prior to commencement to participate in data collection.

This research aims to:

1. Profile the match play demands of adolescent cricket.
2. Advance the understanding of the training loads, stress, fatigue, and recovery associated with preparing and participating for elite adolescent cricket competition.
3. Identify the effect of different physical preparations on markers of stress, fatigue, and recovery and competition performance in elite adolescent cricket players.

The paper is designed for publication in scientific journals. All data will be reported as group average data and no reference will be made to individuals.

As a participant in this study you are free to refuse consent altogether without the need to justify your decision. You are also able to withdraw consent and discontinue participation in the study at any time without giving a reason.

Confidentiality will be protected throughout the duration of this study. Players will be provided with their individual results and encouraged to share their results with their coach for the purposes of performance improvement. All data will be stored at the ACU campus in Strathfield and destroyed in the appropriate time and manner as directed by the university policies.

Any questions regarding this project should be directed to the Principal Investigator and the Student Researcher:

Names and Titles: Dr Tim Gabbett & Mr Dean McNamara.....
Telephone number: 0402 696 496
School: Exercise Science (Brisbane and Strathfield).....
Campus Address: 25A Barker Rd, Strathfield, NSW & 1100 Nudgee Rd, Banyo, QLD
.....

This study has been granted approval by the Australian Catholic University ethics committee.

In the event that you have any complaint or concern, or if you have any query that the Investigator (or Supervisor and Student Researcher) has not been able to satisfy, you may write to the Chair of the Human Research Ethics Committee care of the nearest branch of the Research Services Office.

VIC: Chair, HREC
C/- Research Services
Australian Catholic University
Melbourne Campus
Locked Bag 4115
FITZROY VIC 3065
Tel: 03 9953 3158
Fax: 03 9953 3315

QLD: Chair, HREC
C/- Research Services
Australian Catholic University
Brisbane Campus
PO Box 456
Virginia QLD 4014
Tel: 07 3623 7429
Fax: 07 3623 7328

NSW and ACT: Chair, HREC
C/- Research Services
Australian Catholic University
North Sydney Campus
PO Box 968
NORTH SYDNEY NSW 2059
Tel: 02 9739 2105
Fax: 02 9739 2870

Any complaint or concern will be treated in confidence and fully investigated. You will be informed of the outcome.

If you agree to participate in this project, you should sign both copies of the Consent Form, retain one copy for your records and return the other copy to the Principal Investigator (or Supervisor) or Student Researcher.



Dr Tim Gabbett
Principal Investigator



Mr Dean McNamara
Student Researcher

CONSENT FORM

Copy for Participant to Keep

TITLE OF PROJECT: Physical preparation and competition workloads and fatigue responses of elite junior cricket players

PRINCIPAL INVESTIGATOR: Dr Tim Gabbett

STUDENT RESEARCHER: Mr Dean McNamara

I (the participant) have read (or, where appropriate, have had read to me) and understood the information provided in the Letter to Participants. Any questions I have asked have been answered to my satisfaction. I agree to participate in this project in the 6-8 weeks leading into and during the national championships.

I understand (please tick)

- if I agree to participate in this project I will be contacted by the researchers
video analysis will be taken
data collection will include GPS monitors, saliva samples , countermovement jumps and the completion of questionnaires.
data collected by Cricket NSW may be used in the publication of this research.

I realise that I can withdraw my consent at any time without adverse consequences. I agree that research data collected for the study may be published or may be provided to other researchers in a form that does not identify me in any way. I agree that results may be shared amongst coaches for player analysis purposes.

NAME OF PARTICIPANT:

SIGNATURE

DATE

SIGNATURE OF PRINCIPAL INVESTIGATOR

DATE:.....

SIGNATURE OF STUDENT RESEARCHER:.....

DATE:.....

PARENT/GUARDIAN CONSENT FORM

Copy for Researcher

TITLE OF PROJECT: Physical preparation and competition workloads and fatigue responses of elite junior cricket players

PRINCIPAL INVESTIGATOR: Dr Tim Gabbett

STUDENT RESEARCHER: Mr Dean McNamara

I (the parent/guardian) have read (or, where appropriate, have had read to me) and understood the information provided in the Letter to Participants. Any questions I have asked have been answered to my satisfaction. I agree that my child, nominated below may participate in this project in the 6-8 weeks leading into and during the national championships.

I understand (please tick)

- if I agree to participate in this project my child will be contacted by the researchers
video analysis will be taken
data collection will include GPS monitors, saliva samples , countermovement jumps and the completion of questionnaires.
data collected by Cricket NSW may be used in the publication of this research.

I realise that I can withdraw my consent at any time without adverse consequences. I agree that research data collected for the study may be published or may be provided to other researchers in a form that does not identify my child in any way. I agree that results may be shared amongst coaches for player analysis purposes.

NAME OF PARENT/GUARDIAN:

SIGNATURE

.....

DATE:

NAME OF CHILD

SIGNATURE OF PRINCIPAL INVESTIGATOR:

DATE:.....

SIGNATURE OF STUDENT RESEARCHER:

DATE:

ASSENT OF PARTICIPANTS AGED UNDER 18 YEARS

I (the participant aged under 18 years) understand what this research project is designed to explore. What I will be asked to do has been explained to me. I agree to take part 6-8 weeks leading into and during the national championships and understand that video, GPS, and salivary analysis, countermovement jumps, and completion of questionnaires will take place, realising that I can withdraw at any time without having to give a reason for my decision. I agree that results may be shared amongst coaches for player analysis purposes.

NAME OF PARTICIPANT AGED UNDER 18:

SIGNATURE:..... DATE:

SIGNATURE OF PRINCIPAL INVESTIGATOR:

DATE:

SIGNATURE OF STUDENT RESEARCHER:

DATE:

Chapter 4 - The validity of microsensors to automatically detect bowling events and counts in cricket fast bowlers

INFORMATION LETTER TO PARTICIPANTS

TITLE OF PROJECT: The validity of microsensors to automatically detect bowling events and counts in cricket fast bowlers.....

PRINCIPAL INVESTIGATOR: Dr Tim Gabbett

STUDENT RESEARCHER : Mr Dean McNamara

PROGRAMME IN WHICH ENROLLED: ...Ph.D.....

Dear Participant,

You are invited to participate in a research project designed for Fast Bowlers participating at an elite/semi-elite level of cricket. The purpose of this study is to validate the various methods of identifying and quantifying workloads in fast bowlers. This project will take place throughout the 2012/13 cricket season. The researchers will collect data regarding the loads experienced whilst bowling in training and match settings. Workload and performance variables will be taken throughout the study involving video and GPS analysis, RPE based questionnaires and timed events. This research is for a PhD project and will lead to a thesis.

The study will have minimal inconvenience on your preparation with much of the data already a part of the normal screening procedures undertaken by your state organisation. Testing will occur at scheduled training and during the national cricket championships. Questionnaires will be completed at a time that best fits in with the participant. If any participant suffers physical injury or psychological stress during the duration of this project they will be directed to the preferred and relevant services providers of Cricket NSW.

As a participant you will be asked if you are willing to wear a GPS unit throughout training and competition. The GPS units are small matchbox sized units worn in a foam pouch between your shoulder blades Video analysis will also take place during the competition phase of the data collection. All data will be stored on the university campus, in Strathfield.

Benefits from participation include enhanced and comprehensive workload analysis. Risk to any participant is minimal as no athlete will be asked to do more than their current training and match workload set out by the state coaches.

It is possible that you will be asked to attend training sessions up to 30min prior to commencement to participate in data collection.

This research aims to:

1. Validate new methods of identifying fast bowling workloads.
2. Advance the understanding and reporting of fast bowling workloads for physical conditioning and injury prevention.

The paper is designed for publication in scientific journals. All data will be reported as group average data and no reference will be made to individuals.

As a participant in this study you are free to refuse consent altogether without the need to justify your decision. You are also able to withdraw consent and discontinue participation in the study at any time without giving a reason.

Confidentiality will be protected throughout the duration of this study. Players will be provided with their individual results and encouraged to share their results with their coach for the purposes of performance improvement. All data will be stored at the ACU campus in Strathfield and destroyed in the appropriate time and manner as directed by the university policies.

Any questions regarding this project should be directed to the Principal Investigator and the Student Researcher:

Names and Titles: Dr Tim Gabbett & Mr Dean McNamara.....
Telephone number: 0402 696 496
School: Exercise Science (Brisbane and Strathfield).....
Campus Address: 25A Barker Rd, Strathfield, NSW & 1100 Nudgee Rd, Banyo, QLD.....

This study has been granted approval by the Australian Catholic University ethics committee.

In the event that you have any complaint or concern, or if you have any query that the Investigator (or Supervisor and Student Researcher) has not been able to satisfy, you may write to the Chair of the Human Research Ethics Committee care of the nearest branch of the Research Services Office.

VIC: Chair, HREC
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C/- Research Services
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Fax: 07 3623 7328

NSW and ACT: Chair, HREC
C/- Research Services
Australian Catholic University
North Sydney Campus
PO Box 968
NORTH SYDNEY NSW 2059
Tel: 02 9739 2105
Fax: 02 9739 2870

Any complaint or concern will be treated in confidence and fully investigated. You will be informed of the outcome.

If you agree to participate in this project, you should sign both copies of the Consent Form, retain one copy for your records and return the other copy to the Principal Investigator (or Supervisor) or Student Researcher.

Dr Tim Gabbett
Principal Investigator

Mr Dean McNamara
Student Researcher

CONSENT FORM

Copy for Participant to Keep

TITLE OF PROJECT: The validity of microsensors to automatically detect bowling events and counts in cricket fast bowlers.....
.....

PRINCIPAL INVESTIGATOR: Dr Tim Gabbett

STUDENT RESEARCHER: Mr Dean McNamara

I *(the participant)* have read *(or, where appropriate, have had read to me)* and understood the information provided in the Letter to Participants. Any questions I have asked have been answered to my satisfaction.

I understand (please tick)

- if I agree to participate in this project I will be contacted by the researchers
- video analysis will be taken
- data collection will include GPS monitors, timing measures, .
- data collected by Cricket NSW may be used in the publication of this research.

I realise that I can withdraw my consent at any time without adverse consequences. I agree that research data collected for the study may be published or may be provided to other researchers in a form that does not identify me in any way. I agree that results may be shared amongst coaches for player analysis purposes.

NAME OF PARTICIPANT:

SIGNATURE

DATE

.....

SIGNATURE OF PRINCIPAL INVESTIGATOR

DATE:.....

SIGNATURE OF STUDENT RESEARCHER:

DATE:.....

CONSENT FORM

Copy for Researcher to Keep

TITLE OF PROJECT: Validation of wearable microtechnology units for detecting cricket fast bowling events

PRINCIPAL INVESTIGATOR: Dr Tim Gabbett

STUDENT RESEARCHER: Mr Dean McNamara

I (the participant) have read (or, where appropriate, have had read to me) and understood the information provided in the Letter to Participants. Any questions I have asked have been answered to my satisfaction.

I understand (please tick)

- if I agree to participate in this project I will be contacted by the researchers
video analysis will be taken
data collection will include GPS monitors, timing measures, .
data collected by Cricket NSW may be used in the publication of this research.

I realise that I can withdraw my consent at any time without adverse consequences. I agree that research data collected for the study may be published or may be provided to other researchers in a form that does not identify me in any way. I agree that results may be shared amongst coaches for player analysis purposes.

NAME OF PARTICIPANT:

SIGNATURE

DATE

SIGNATURE OF PRINCIPAL INVESTIGATOR

DATE:.....

SIGNATURE OF STUDENT RESEARCHER:

DATE:.....

Chapter 5 - Variability of Player Load™, bowling velocity, and performance execution in fast bowlers across repeated bowling spells

INFORMATION LETTER TO PARTICIPANTS

TITLE OF PROJECT: Variability of Player Load™, bowling velocity, and performance execution in fast bowlers across repeated bowling spells

PRINCIPAL INVESTIGATOR: Dr Tim Gabbett

STUDENT RESEARCHER : Mr Dean McNamara

PROGRAMME IN WHICH ENROLLED: ...Ph.D.....

Dear Participant,

You are invited to participate in a research project designed for Fast Bowlers participating at an elite/semi-elite level of cricket. The purpose of this study is to identify the stability of wearable microtechnology variables, bowling velocity, and performance execution in fast bowlers across repeated bowling spells. This project will take place throughout the 2013/14 cricket preseason. The researchers will collect data regarding the loads experienced whilst bowling in training and the resultant bowling performance. Workload and performance variables will be taken throughout the study involving GPS analysis, ball velocity and bowling execution scores. This research is for a PhD project and will lead to a thesis.

The study will have minimal inconvenience on your preparation with much of the data already a part of the normal screening procedures undertaken by your state organisation. Testing will occur at scheduled training sessions. Questionnaires will be completed at a time that best fits in with the participant. If any participant suffers physical injury or psychological stress during the duration of this project they will be directed to the preferred and relevant services providers of Cricket NSW.

As a participant you will be asked if you are willing to wear a GPS unit throughout training. The GPS units are small matchbox sized units worn in a foam pouch between your shoulder blades Video analysis will also take place during the competition phase of the data collection. All data will be stored on the university campus, in Strathfield.

Benefits from participation include enhanced and comprehensive workload analysis. Risk to any participant is minimal as no athlete will be asked to do more than their current training and match workload set out by the state coaches.

It is possible that you will be asked to attend training sessions up to 30min prior to commencement to participate in data collection.

This research aims to:

To identify the stability of microtechnology outputs during repeated fast bowling events.

The paper is designed for publication in scientific journals. All data will be reported as group average data and no reference will be made to individuals.

As a participant in this study you are free to refuse consent altogether without the need to justify your decision. You are also able to withdraw consent and discontinue participation in the study at any time without giving a reason.

Confidentiality will be protected throughout the duration of this study. Players will be provided with their individual results and encouraged to share their results with their coach for the purposes of performance improvement. All data will be stored at the ACU campus in Strathfield and destroyed in the appropriate time and manner as directed by the university policies.

Any questions regarding this project should be directed to the Principal Investigator and the Student Researcher:

Names and Titles: Dr Tim Gabbett & Mr Dean McNamara.....
Telephone number: 0402 696 496
School: Exercise Science (Brisbane and Strathfield).....
Campus Address: 25A Barker Rd, Strathfield, NSW & 1100 Nudgee Rd, Banyo, QLD.....

This study has been granted approval by the Australian Catholic University ethics committee.

In the event that you have any complaint or concern, or if you have any query that the Investigator (or Supervisor and Student Researcher) has not been able to satisfy, you may write to the Chair of the Human Research Ethics Committee care of the nearest branch of the Research Services Office.

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NSW and ACT: Chair, HREC
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Australian Catholic University
North Sydney Campus
PO Box 968
NORTH SYDNEY NSW 2059
Tel: 02 9739 2105
Fax: 02 9739 2870

Any complaint or concern will be treated in confidence and fully investigated. You will be informed of the outcome.

If you agree to participate in this project, you should sign both copies of the Consent Form, retain one copy for your records and return the other copy to the Principal Investigator (or Supervisor) or Student Researcher.



Dr Tim Gabbett
Principal Investigator



Mr Dean McNamara
Student Researcher

CONSENT FORM

Copy for Participant to Keep

TITLE OF PROJECT: Variability of Player Load™, bowling velocity, and performance execution in fast bowlers across repeated bowling spells

PRINCIPAL INVESTIGATOR: Dr Tim Gabbett

STUDENT RESEARCHER: Mr Dean McNamara

I (the participant) have read (or, where appropriate, have had read to me) and understood the information provided in the Letter to Participants. Any questions I have asked have been answered to my satisfaction.

I understand (please tick)

- if I agree to participate in this project I will be contacted by the researchers
- video analysis will be taken
- data collection will include GPS monitors, timing measures.
- data collected by Cricket NSW may be used in the publication of this research.

I realise that I can withdraw my consent at any time without adverse consequences. I agree that research data collected for the study may be published or may be provided to other researchers in a form that does not identify me in any way. I agree that results may be shared amongst coaches for player analysis purposes.

NAME OF PARTICIPANT:

SIGNATURE

DATE

.....

SIGNATURE OF PRINCIPAL INVESTIGATOR

DATE:.....

SIGNATURE OF STUDENT RESEARCHER:

DATE:.....

CONSENT FORM

Copy for Researcher to Keep

TITLE OF PROJECT: Variability of Player Load™, bowling velocity, and performance execution in fast bowlers across repeated bowling spells

PRINCIPAL INVESTIGATOR: Dr Tim Gabbett

STUDENT RESEARCHER: Mr Dean McNamara

I (the participant) have read (or, where appropriate, have had read to me) and understood the information provided in the Letter to Participants. Any questions I have asked have been answered to my satisfaction.

I understand (please tick)

- if I agree to participate in this project I will be contacted by the researchers
- video analysis will be taken
- data collection will include GPS monitors, timing measures.
- data collected by Cricket NSW may be used in the publication of this research.

I realise that I can withdraw my consent at any time without adverse consequences. I agree that research data collected for the study may be published or may be provided to other researchers in a form that does not identify me in any way. I agree that results may be shared amongst coaches for player analysis purposes.

NAME OF PARTICIPANT:

SIGNATURE

DATE

.....

SIGNATURE OF PRINCIPAL INVESTIGATOR

DATE:.....

SIGNATURE OF STUDENT RESEARCHER:

DATE:.....

Chapter 6 - Relationship between wearable microtechnology device variables and cricket fast bowling intensity

INFORMATION LETTER TO PARTICIPANTS

TITLE OF PROJECT: Relationship between wearable microtechnology device variables and cricket fast bowling intensity.....

PRINCIPAL INVESTIGATOR: Dr Tim Gabbett

STUDENT RESEARCHER : Mr Dean McNamara

PROGRAMME IN WHICH ENROLLED: ...Ph.D.....

Dear Participant,

You are invited to participate in a research project designed for Fast Bowlers participating at an elite/semi-elite level of cricket. The purpose of this study is to examine relationships between wearable microtechnology device variables and cricket fast bowling intensity. This project will take place throughout the 2013/14 cricket preseason. The researchers will collect data regarding the loads experienced whilst bowling in training, measures of bowling execution, and ball velocity. Bowling intensity will be performed by at a predetermined intensity and measures of microtechnology outputs and ball velocity will be used to quantify bowling intensity. This research is for a PhD project and will lead to a thesis.

The study will have minimal inconvenience on your preparation with much of the data already a part of the normal training and screening completed in training. Testing will occur at scheduled training sessions. If any participant suffers physical injury or psychological stress during the duration of this project they will be directed to the preferred and relevant services providers of Cricket NSW/Cricket Australia.

As a participant you will be asked if you are willing to wear a GPS unit throughout training. The GPS units are small matchbox sized units worn in a foam pouch between your shoulder blades Video analysis will also take place during the competition phase of the data collection. All data will be stored on the university campus, in Strathfield.

Benefits from participation include enhanced and comprehensive workload analysis. Risk to any participant is minimal as no athlete will be asked to do more than their current training and match workload set out by the state coaches.

It is possible that you will be asked to attend training sessions up to 30min prior to commencement to participate in data collection.

This research aims to:

To identify the stability of microtechnology outputs during repeated fast bowling events.

The paper is designed for publication in scientific journals. All data will be reported as group average data and no reference will be made to individuals.

As a participant in this study you are free to refuse consent altogether without the need to justify your decision. You are also able to withdraw consent and discontinue participation in the study at any time without giving a reason.

Confidentiality will be protected throughout the duration of this study. Players will be provided with their individual results and encouraged to share their results with their coach for the purposes of performance improvement. All data will be stored at the ACU campus in Strathfield and destroyed in the appropriate time and manner as directed by the university policies.

Any questions regarding this project should be directed to the Principal Investigator and the Student Researcher:

Names and Titles: Dr Tim Gabbett & Mr Dean McNamara.....
Telephone number: 0402 696 496
School: Exercise Science (Brisbane and Strathfield).....
Campus Address: 25A Barker Rd, Strathfield, NSW & 1100 Nudgee Rd, Banyo, QLD.....

This study has been granted approval by the Australian Catholic University ethics committee.

In the event that you have any complaint or concern, or if you have any query that the Investigator (or Supervisor and Student Researcher) has not been able to satisfy, you may write to the Chair of the Human Research Ethics Committee care of the nearest branch of the Research Services Office.

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Fax: 07 3623 7328

NSW and ACT: Chair, HREC
C/- Research Services
Australian Catholic University
North Sydney Campus
PO Box 968
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Tel: 02 9739 2105
Fax: 02 9739 2870

Any complaint or concern will be treated in confidence and fully investigated. You will be informed of the outcome.

If you agree to participate in this project, you should sign both copies of the Consent Form, retain one copy for your records and return the other copy to the Principal Investigator (or Supervisor) or Student Researcher.

Dr Tim Gabbett
Principal Investigator

Mr Dean McNamara
Student Researcher

CONSENT FORM

Copy for Participant to Keep

TITLE OF PROJECT: Relationship between wearable microtechnology device variables and cricket fast bowling intensity

PRINCIPAL INVESTIGATOR: Dr Tim Gabbett

STUDENT RESEARCHER: Mr Dean McNamara

I (*the participant*) have read (*or, where appropriate, have had read to me*) and understood the information provided in the Letter to Participants. Any questions I have asked have been answered to my satisfaction.

I understand (please tick)

- if I agree to participate in this project I will be contacted by the researchers
- video analysis will be taken
- data collection will include GPS monitors, timing measures.
- data collected by Cricket NSW may be used in the publication of this research.

I realise that I can withdraw my consent at any time without adverse consequences. I agree that research data collected for the study may be published or may be provided to other researchers in a form that does not identify me in any way. I agree that results may be shared amongst coaches for player analysis purposes.

NAME OF PARTICIPANT:

SIGNATURE

DATE

.....

SIGNATURE OF PRINCIPAL INVESTIGATOR

DATE:.....

SIGNATURE OF STUDENT RESEARCHER:

DATE:.....

CONSENT FORM

Copy for Researcher to Keep

TITLE OF PROJECT: Relationship between wearable microtechnology device variables and cricket fast bowling intensity

PRINCIPAL INVESTIGATOR: Dr Tim Gabbett

STUDENT RESEARCHER: Mr Dean McNamara

I (the participant) have read (or, where appropriate, have had read to me) and understood the information provided in the Letter to Participants. Any questions I have asked have been answered to my satisfaction.

I understand (please tick)

- if I agree to participate in this project I will be contacted by the researchers
- video analysis will be taken
- data collection will include GPS monitors, timing measures.
- data collected by Cricket NSW may be used in the publication of this research.

I realise that I can withdraw my consent at any time without adverse consequences. I agree that research data collected for the study may be published or may be provided to other researchers in a form that does not identify me in any way. I agree that results may be shared amongst coaches for player analysis purposes.

NAME OF PARTICIPANT:

SIGNATURE

DATE

.....

SIGNATURE OF PRINCIPAL INVESTIGATOR

DATE:.....

SIGNATURE OF STUDENT RESEARCHER:

DATE:.....

Ethics Approvals

Appendix D - Approval ID: Q2011 65

Human Research Ethics Committee

Committee Approval Form

Principal Investigator/Supervisor: Timothy Gabbett

Co-Investigators:

Student Researcher: : Dean McNamara

Ethics approval has been granted for the following project:

Profiling fatigue variables during preparation and competition of adolescent male national cricket championships (Profiling fatigue variables in adolescent cricketers)

for the period: 30 September 2011 to 29 February 2012

Human Research Ethics Committee (HREC) Register Number: Q2011 65

Special Condition/s of Approval

Prior to commencement of your research, the following permissions are required to be submitted to the ACU HREC:

Cricket NSW (Received)

The following standard conditions as stipulated in the *National Statement on Ethical Conduct in Research Involving Humans (2007)* apply:

- (i) that Principal Investigators / Supervisors provide, on the form supplied by the Human Research Ethics Committee, annual reports on matters such as:
 - security of records
 - compliance with approved consent procedures and documentation
 - compliance with special conditions, and

- (ii) that researchers report to the HREC immediately any matter that might affect the ethical acceptability of the protocol, such as:
 - proposed changes to the protocol
 - unforeseen circumstances or events

- adverse effects on participants

The HREC will conduct an audit each year of all projects deemed to be of more than low risk. There will also be random audits of a sample of projects considered to be of negligible risk and low risk on all campuses each year.

Within one month of the conclusion of the project, researchers are required to complete a *Final Report Form* and submit it to the local Research Services Officer.

If the project continues for more than one year, researchers are required to complete an *Annual Progress Report Form* and submit it to the local Research Services Officer within one month of the anniversary date of the ethics approval.



Signed: Date:
30.09.2011.....

(Research Services Officer, McAuley Campus)

From: Kylie Pashley <Kylie.Pashley@acu.edu.au>
Sent: Friday, 30 September 2011 2:27 PM
To: Timothy James Gabbett; Dean McNamara
Cc: Kylie Pashley
Subject: Application approved

Dear Tim and Dean,

Q2011 65
Profiling fatigue variables during preparation and competition of adolescent male national cricket championships (Profiling fatigue variables in adolescent cricketers)

The Australian Catholic University Human Research Ethics Committee has reviewed the ethics application number Q2011 65 Profiling fatigue variables during preparation and competition of adolescent male national cricket championships (Profiling fatigue variables in adolescent cricketers) . In all future correspondence with the Committee please quote the ACU reference number Q2011 65 .

The Chair of the Expedited Review Panel has considered your application and any subsequent response to queries raised and has granted ethics approval. The approved period of data collection is 30/09/2011 to 29/02/2012.

Please note the following conditions of approval.

1. Any departure from the protocol detailed in your proposal must be reported immediately to the Committee.
2. When you propose a change to an approved protocol, which you consider to be minor, you are required to submit a modification form for approval to the Chairperson, through the appropriate Research Ethics Officer. Where substantive changes to any approved protocols are proposed, you are required to submit a full, new proposal for consideration by the ACU HREC.
3. You are required to notify the Research Ethics Officer of any serious adverse events or complaints.
4. Under the NHMRC National Statement on Ethics Conduct in Research Involving Humans (<http://www.nhmrc.gov.au/publications/synopses/e72syn.htm>) research ethics committees are responsible for monitoring approved research to ensure continued compliance with ethical standards. You are required to provide a written report on the progress of the approved project annually. The proforma report is available from http://www.acu.edu.au/about_acu/research/for_researchers/research_ethics/ and download 'Progress/Final/Extension Report Form for Research Projects'.
5. The Committee may choose to conduct an interim audit of your research.
6. The decision is subject to ratification at the next available committee meeting. You will only be contacted again in relation to this matter if the Committee raises any additional questions or concerns in regard to the clearance.

I have attached an electronic copy of the Approval Form.

We wish you well in this research project.

Kind regards,
Kylie Pashley

Ethics Officer | Research Services
Office of the Deputy Vice Chancellor (Research)
Australian Catholic University
PO Box 456, Virginia, QLD, 4014
T: 07 3623 7429 F: 07 3623 7328

THIS IS AN AUTOMATICALLY GENERATED RESEARCHMASTER EMAIL

Appendix E - Approval ID: 2012 296Q



Human Research Ethics Committee
Committee Approval Form

Principal Investigator/Supervisor: Dr Tim Gabbett

Co-Investigators:

Student Researcher: : Dean McNamara

Ethics approval has been granted for the following project:

New methods for identifying fast bowling workloads

for the period: 30/06/2013

Human Research Ethics Committee (HREC) Register Number: 2012 296Q

Special Condition/s of Approval

Prior to commencement of your research, the following permissions are required to be submitted to the ACU HREC:

The data collection of your project has received ethical clearance but the decision and authority to commence may be dependent on factors beyond the remit of the ethics review process and approval is subject to ratification at the next available Committee meeting. The Chief Investigator is responsible for ensuring that outstanding permission letters are obtained, interview/survey questions, if relevant, and a copy forwarded to ACU HREC before any data collection can occur. Failure to provide outstanding documents to the ACU HREC before data collection commences is in breach of the National Statement on Ethical Conduct in Human Research and the Australian Code for the Responsible Conduct of Research. Further, this approval is only valid as long as approved procedures are followed.

Clinical Trials: You are required to register it in a publicly accessible trials registry prior to enrolment of the first participant (e.g. Australian New Zealand Clinical Trials Registry <http://www.anzctr.org.au/>) as a condition of ethics approval.

It is the Principal Investigators / Supervisors responsibility to ensure that:

1. All serious and unexpected adverse events should be reported to the HREC with 72 hours.
2. Any changes to the protocol must be reviewed by the HREC by submitting a Modification/Change to Protocol Form prior to the research commencing or continuing. <http://research.acu.edu.au/researcher-support/integrity-and-ethics/>
3. Progress reports are to be submitted on an annual basis. <http://research.acu.edu.au/researcher-support/integrity-and-ethics/>
4. All research participants are to be provided with a Participant Information Letter and consent form, unless otherwise agreed by the Committee.
5. Protocols can be extended for a maximum of five (5) years after which a new application must be submitted. (The five year limit on renewal of approvals allows the Committee to fully re-review research in an environment where legislation, guidelines and requirements are continually changing, for example, new child protection and privacy laws).

Researchers must immediately report to HREC any matter that might affect the ethical acceptability of the protocol eg: changes to protocols or unforeseen circumstances or adverse effects on participants.

K. Pashley.

Signed:

..... Date: 16/08/2016.....

Subject: Ethics application approved 2012 296Q
Date: 2012-12-11 10:12
From: Res Ethics <Res.Ethics@acu.edu.au>
To: Tim Gabbett <Tim.Gabbett@acu.edu.au>, "Dean McNamara (dean@ssep.com.au)"
<dean@ssep.com.au>
Cc: Kylie Pashley <Kylie.Pashley@acu.edu.au>

Dear Tim and Dean,

Principal Investigator: Dr Timothy James Gabbett Student Researcher: Dean McNamara Ethics Register Number: 2012 296Q Project Title: New methods for identifying fast bowling workloads Risk Level: Low Risk Date Approved: 11/12/2012 Ethics Clearance End Date: 30/06/2013

This email is to advise that your application has been reviewed by the Australian Catholic University's Human Research Ethics Committee and confirmed as meeting the requirements of the National Statement on Ethical Conduct in Human Research.

This project has been awarded ethical clearance until 30/06/2013. In order to comply with the National Statment on Ethical Conduct in Human Research, progress reports are to be submitted on an annual basis. If an extension of time is required researchers must submit a progress report.

Whilst the data collection of your project has received ethical clearance, the decision and authority to commence may be dependent on factors beyond the remit of the ethics review process. For example, your research may need ethics clearance or permissions from other organisations to access staff. Therefore the proposed data collection should not commence until you have satisfied these requirements.

If you require a formal approval certificate, please respond via reply email and one will be issued.

Decisions related to low risk ethical review are subject to ratification at the next available Committee meeting. You will only be contacted again in relation to this matter if the Committee raises any additional questions or concerns.

Researchers who fail to submit an appropriate progress report may have their ethical clearance revoked and/or the ethical clearances of other projects suspended. When your project has been completed please complete and submit a progress/final report form and advise us by email at your earliest convenience. The information researchers provide on the security of records, compliance with approval consent procedures and documentation and responses to special conditions is reported to the NHMRC on an annual basis. In accordance with NHMRC the ACU HREC may undertake annual audits of any projects considered to be of more than low risk.

It is the Principal Investigators / Supervisors responsibility to ensure that:

1. All serious and unexpected adverse events should be reported to the HREC with 72 hours.
2. Any changes to the protocol must be approved by the HREC by submitting a Modification Form prior to the research commencing or continuing.
3. All research participants are to be provided with a Participant Information Letter and consent form, unless otherwise agreed by the Committee.

For progress and/or final reports, please complete and submit a Progress / Final Report form:

http://www.acu.edu.au/about_acu/research/staff/research_ethics/

For modifications to your project, please complete and submit a Modification form:

http://www.acu.edu.au/about_acu/research/staff/research_ethics/

Researchers must immediately report to HREC any matter that might affect the ethical acceptability of the protocol eg: changes to protocols or unforeseen circumstances or adverse effects on participants.

Please do not hesitate to contact the office if you have any queries.

Kind regards,
Gabrielle Ryan

Ethics Officer | Research Services
Office of the Deputy Vice Chancellor (Research) Australian Catholic University

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Appendix F - Approval ID: 2013 154Q



Human Research Ethics Committee
Committee Approval Form

Principal Investigator/Supervisor: Dr Tim Gabbett

Co-Investigators:

Student Researcher: : Dean McNamara

Ethics approval has been granted for the following project:

Influence of Physical Qualities and Bowling History on Fatigue Resistance to Repeated Fast Bowling Efforts

for the period: 30/06/2014

Human Research Ethics Committee (HREC) Register Number: 2013 154Q

Special Condition/s of Approval

Prior to commencement of your research, the following permissions are required to be submitted to the ACU HREC:

The data collection of your project has received ethical clearance but the decision and authority to commence may be dependent on factors beyond the remit of the ethics review process and approval is subject to ratification at the next available Committee meeting. The Chief Investigator is responsible for ensuring that outstanding permission letters are obtained, interview/survey questions, if relevant, and a copy forwarded to ACU HREC before any data collection can occur. Failure to provide outstanding documents to the ACU HREC before data collection commences is in breach of the National Statement on Ethical Conduct in Human Research and the Australian Code for the Responsible Conduct of Research. Further, this approval is only valid as long as approved procedures are followed.

Clinical Trials: You are required to register it in a publicly accessible trials registry prior to enrolment of the first participant (e.g. Australian New Zealand Clinical Trials Registry <http://www.anzctr.org.au/>) as a condition of ethics approval.

It is the Principal Investigators / Supervisors responsibility to ensure that:

1. All serious and unexpected adverse events should be reported to the HREC with 72 hours.
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3. Progress reports are to be submitted on an annual basis. <http://research.acu.edu.au/researcher-support/integrity-and-ethics/>
4. All research participants are to be provided with a Participant Information Letter and consent form, unless otherwise agreed by the Committee.
5. Protocols can be extended for a maximum of five (5) years after which a new application must be submitted. (The five year limit on renewal of approvals allows the Committee to fully re-review research in an environment where legislation, guidelines and requirements are continually changing, for example, new child protection and privacy laws).

Researchers must immediately report to HREC any matter that might affect the ethical acceptability of the protocol eg: changes to protocols or unforeseen circumstances or adverse effects on participants.

A handwritten signature in black ink that reads 'K. Pashley'.

Signed:

.....

Date: 16/08/2016.....

From: Stefania Riccardi <Stefania.Riccardi@acu.edu.au> on behalf of Res Ethics
<Res.Ethics@acu.edu.au>

Sent: Monday, 19 August 2013 11:25 AM

To: Tim Gabbett

Cc: Dean McNamara

Subject: Ethics application 2013 154Q approved!

Dear Applicant,

Principal Investigator: Dr Timothy Gabbett

Student Researcher: Dean McNamara

Ethics Register Number: 2013 154Q

Project Title: Influence of Physical Qualities and Bowling History on Fatigue Resistance to Repeated Fast Bowling Efforts

Risk Level: Low Risk 3

Date Approved: 19/08/2013

Ethics Clearance End Date: 31/12/2013

This email is to advise that your application has been reviewed by the Australian Catholic University's Human Research Ethics Committee and confirmed as meeting the requirements of the National Statement on Ethical Conduct in Human Research.

This project has been awarded ethical clearance until 31/12/2013. In order to comply with the National Statement on Ethical Conduct in Human Research, progress reports are to be submitted on an annual basis. If an extension of time is required researchers must submit a progress report.

Whilst the data collection of your project has received ethical clearance, the decision and authority to commence may be dependent on factors beyond the remit of the ethics review process. For example, your research may need ethics clearance or permissions from other organisations to access staff. Therefore the proposed data collection should not commence until you have satisfied these requirements.

If you require a formal approval certificate, please respond via reply email and one will be issued.

Decisions related to low risk ethical review are subject to ratification at the next available Committee meeting. You will only be contacted again in relation to this matter if the Committee raises any additional questions or concerns.

Researchers who fail to submit an appropriate progress report may have their ethical clearance revoked and/or the ethical clearances of other projects suspended. When your project has been completed please complete and submit a progress/final report form and advise us by email at your earliest convenience. The information researchers provide on the security of records, compliance with approval consent procedures and documentation and responses to special conditions is reported to the NHMRC on an annual basis. In accordance with NHMRC the ACU HREC may undertake annual audits of any projects considered to be of more than low risk.

It is the Principal Investigators / Supervisors responsibility to ensure that:

1. All serious and unexpected adverse events should be reported to the HREC with 72 hours.
2. Any changes to the protocol must be approved by the HREC by submitting a Modification Form prior to the research commencing or continuing.
3. All research participants are to be provided with a Participant Information Letter and consent form, unless otherwise agreed by the Committee.

For progress and/or final reports, please complete and submit a Progress / Final Report form:
www.acu.edu.au/465013

For modifications to your project, please complete and submit a Modification form:
www.acu.edu.au/465013

Researchers must immediately report to HREC any matter that might affect the ethical acceptability of the protocol eg: changes to protocols or unforeseen circumstances or adverse effects on participants.

Please do not hesitate to contact the office if you have any queries.

Kind regards,
Stefania Riccardi

Ethics Officer | Research Services
Office of the Deputy Vice Chancellor (Research) Australian Catholic University

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Appendix G - Strobe quality of assessment

Authors	1. inclusion criteria were clearly stated;	2. intervention was clearly defined;	3. groups were tested for similarity at baseline;	4. outcome variables were clearly defined;	5. assessments were practically useful;	6. duration of intervention practically useful;	7. statistical analysis appropriate;	8. point measures of variability.	SCORE	%
Pyne et al. (2006)	2	2	2	2	1	2	2	2	15	94%
Duffield et al. (2009)	2	2	2	2	1	2	2	2	15	94%
Orchard et al. (2009)	2	2	1	2	2	2	2	0	13	81%
Johnstone et al. (2010)	1	2	1	2	1	2	2	0	11	69%
Orchard et al. (2010)	2	2	1	2	1	2	2	1	13	81%
Orchard et al. (2010)	1	1	1	1	1	2	0	0	7	44%
Petersen et al. (2010)	2	2	1	2	2	2	2	2	15	94%
Petersen et al. (2011)	2	2	1	2	2	2	2	2	15	94%
Petersen et al. (2011)	2	1	1	2	2	2	2	2	14	88%
Lombard et al. (2012)	2	2	2	1	1	1	1	0	10	63%
Phillips et al. (2012)	2	2	1	2	1	1	2	1	12	75%
McNamara et al. (2013)	2	2	1	2	2	1	2	2	14	88%
Ranson et al. (2013)	2	2	1	2	1	2	0	0	10	63%
Hulin et al. (2014)	2	2	1	2	2	2	2	1	14	88%
McNamara et al. (2015)	1	2	1	2	2	2	2	1	13	93%
Orchard et al. (2015)	2	2	1	2	2	2	2	1	14	88%
Orchard et al. (2015)	2	2	1	2	2	2	2	1	14	88%

Appendix H - Invited Speaker Presentations

- (i) 2nd ASPIRE SPORT SCIENCE CONFERENCE “Monitoring Athlete Training Loads – The Hows and Whys” 23rd to 25th February 2016. Doha, QATAR
- (ii) Cricket Australia Working Groups Conference. May 2016. Brisbane, AUSTRALIA
- (iii) Sydney Strength and Conditioning Working Group. November, 2015. Sydney, AUSTRALIA
- (iv) Cricket Australia Working Groups Conference. May, 2015. Brisbane, AUSTRALIA

2nd ASPIRE SPORT SCIENCE CONFERENCE “Monitoring Athlete Training Loads – The Hows and Whys” 23rd to 25th February 2016. Doha, QATAR

The use of wearable microtechnology to monitor workload in cricket fast bowlers

Dean McNamara
 Tim Gabbett
 Geraldine Naughton

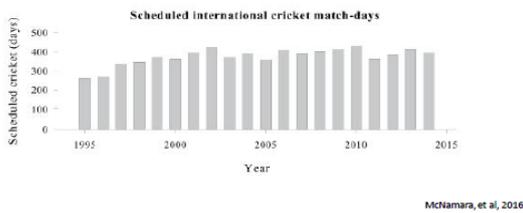
2nd ASPIRE SPORT SCIENCE CONFERENCE
 “Monitoring Athlete Training Loads - The Hows and Whys”
 23rd to 25th February 2016, Doha QATAR



Overview

1. Introduction to Fast Bowling Workloads
- 2a. Automated Bowling Counts via Wearable Microtechnology
- 2b. Microtechnology and Fast Bowling Intensity

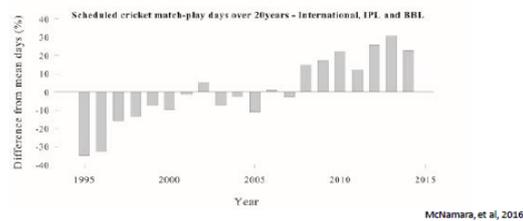
Matchplay Days in the year



Cricket Competitions

- 3 forms of cricket:
 - Multiday cricket (4-5 days)
 - 50-over cricket (8 hours)
 - 20-over cricket (3 hours)

Matchplay Days in the year – Including Domestic T20



Workload of Fast Bowlers in Elite Cricket

External workload measures in fast bowlers

1. GPS tracking
 Total distance and distance across speed zones
2. Counting balls bowled
 Monitoring specific fast bowling workload

GPS Tracking in Cricket

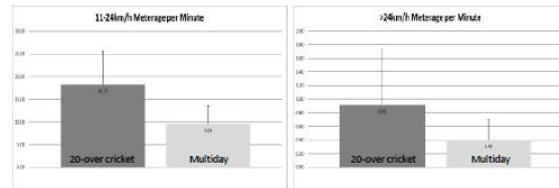
- Between cricketers
 - Fast bowlers have the greatest workload over all over cricket positions

Petersen, et al. 2010, McNamee, et al. 2013

- Between competition type
 - Multiday cricket has the greatest volume of workload
 - Twenty20 cricket has the greatest intensity

Petersen, et al. 2010

GPS Tracking in Cricket – BBL vs Sheffield Shield 2015/16



Counting Balls Bowled

- Injury and bowling workload relationship has been established
 - Dennis, et al 2003, Orchard, et al 2009, Hulin, et al 2013
- Routinely used to measure bowling load in Australian fast bowlers
- Simple collection of data
- Calculation of acute and chronic bowling loads

Fast Bowling Injury in Cricket



Fast Bowling Injury in Cricket

- Fast bowling generates both injury risk and resilience
 - Dennis, et al, 2003
- Acute load bowling spikes of >150% increase injury likelihood
 - Hulin, et al, 2013
- Bowling workload history appears to have complex interaction with likelihood of injury type
 - Orchard, et al, 2015

Refining Workload in Fast Bowlers – Fast Bowling Preparedness

- Acute loads (7day) and chronic loads (28 day average) are routinely used amongst elite Australian cricketers



Challenges of Elite Fast Bowling Workload Management – in the real world

Training	Environment	Competition	Physical
<ul style="list-style-type: none"> • Skill Acquisition • Age • Indoor Facilities • Outdoor Facilities 	<ul style="list-style-type: none"> • Pitch Conditions • Country • Weather 	<ul style="list-style-type: none"> • T20 • 50-Over • Multiday formats • Team/Franchise • Injury to team mate • Tactical Decisions • Player Performance <ul style="list-style-type: none"> • Selection • Yearly Schedule 	<ul style="list-style-type: none"> • Bone Maturation • Rules and restrictions • Injury

Challenges of Elite Fast Bowling Workload Management – in the real world

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Challenges of Elite Fast Bowling Workload Management – in the real world

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Advancing the Methodology of Bowling Workload Measures



Automated Bowling Counts via Wearable Microtechnology



Automated Bowling Counts via Wearable Microtechnology

		Ball Bowled during training (as determined by direct bowling count)	
		Ball Bowled	Ball Not Bowled
Automatic detection of ball bowled during training	Bowling Event Automatically Detected	True Positives = 289	False Positives = 1
	Bowling Event NOT Automatically Detected	False Negatives = 2	True Negatives = 117
		Sensitivity = 99.4%	Specificity = 98.1%
		Ball Bowled during competition (as determined by direct bowling count)	
		Ball Bowled	Ball Not Bowled
Automatic detection of ball bowled during competition	Bowling Event Automatically Detected	True Positives = 114	False Positives = 24
	Bowling Event NOT Automatically Detected	False Negatives = 1	True Negatives = 47
		Sensitivity = 99.1%	Specificity = 74.0%

McNamara, et al, 2014

Automated Bowling Counts via Wearable Microtechnology

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Automatic detection of ball bowled during training	Bowling Event Automatically Detected	True Positives = 289	False Positives = 1
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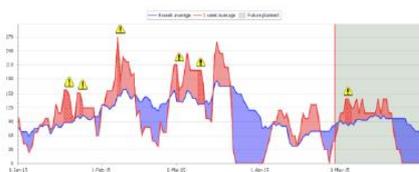
McNamara, et al, 2014

Automated Bowling Counts via Wearable Microtechnology

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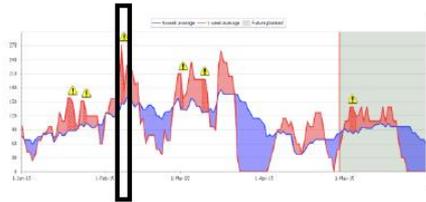
Meaningfulness of a Bowling Load



Are they all the same - Ball Counting

- Assumption that all balls are delivered with the same intensity
- Possibly fail to account for the range in bowling intensities
- Collecting ball velocity is not practical

Meaningfulness of a Bowling Load



Microtechnology and Fast Bowling Intensity

- Prescribed efforts of 60%, 70%, 85% & 100%
- Relative scores of
 - PlayerLoad™
 - Roll
 - Yaw
 - Resultant Accelerometer
- Ball Velocity



Microtechnology and Fast Bowling Intensity

Prescribed Effort Relationship	R	Ball Velocity Relationship	R
Resultant max %	0.71 ± 0.28 Very Large	Resultant max %	0.64 ± 0.33 Large
Player Load™ max %	0.83 ± 0.19 Very Large	Player Load™ max %	0.82 ± 0.20 Very Large
Roll max %	0.80 ± 0.21 Very Large	Roll max %	0.73 ± 0.27 Very Large
Yaw max %	0.56 ± 0.37 Large	Yaw max %	0.58 ± 0.36 Large

Polynomial regression ± 90% confidence intervals and descriptor.

Microtechnology and Fast Bowling Intensity

Prescribed Effort Relationship	R	Ball Velocity Relationship	R
Resultant max %	0.71 ± 0.28 Very Large	Resultant max %	0.64 ± 0.33 Large
Player Load™ max %	0.83 ± 0.19 Very Large	Player Load™ max %	0.82 ± 0.20 Very Large
Roll max %	0.80 ± 0.21 Very Large	Roll max %	0.73 ± 0.27 Very Large
Yaw max %	0.56 ± 0.37 Large	Yaw max %	0.58 ± 0.36 Large

Polynomial regression ± 90% confidence intervals and descriptor.

Microtechnology Outputs have very large relationships with bowling effort and ball velocity

Microtechnology and Fast Bowling Intensity

Variable	Bowling Intensity %			
	60%	70%	85%	100%
Peak Roll %	Mean 64.4% CV(%) 16.0 (14.0–18.0)	Mean 74.9% CV(%) 11.0 (10.0–13.0)	Mean 88.0% CV(%) 11.0 (9.3.0–12.0)	Mean 93.2% CV(%) 6.1 (5.4–7.1)
Peak Accelerometer resultant %	Mean 57.0% CV(%) 21.0 (19.0–24.0)	Mean 72.2% CV(%) 17.0 (15.0–19.0)	Mean 81.0% CV(%) 12.0 (10.0–13.0)	Mean 86.4% CV(%) 12.0 (10.0–13.0)
Peak Player Load™ %	Mean 56.7% CV(%) 19.0 (17.0–23.0)	Mean 68.8% CV(%) 14.0 (12.0–16.0)	Mean 81.4% CV(%) 9.6 (8.4–11.0)	Mean 92.1% CV(%) 7.3 (6.4–8.5)
Peak Yaw %	Mean 72.8% CV(%) 22.0 (19.0–26.0)	Mean 82.6% CV(%) 16.0 (14.0–18.0)	Mean 91.2% CV(%) 10.0 (9.1–12.0)	Mean 93.3% CV(%) 8.4 (7.4–9.7)
Relative Ball Velocity %	Mean 81.9% CV(%) 6.6 (5.8–7.7)	Mean 89.3% CV(%) 3.8 (3.4–4.4)	Mean 93.3% CV(%) 3.6 (3.2–4.2)	Mean 97.2% CV(%) 2.6 (2.3–3.0)

Coefficient of variation (CV%) and 90% confidence interval.

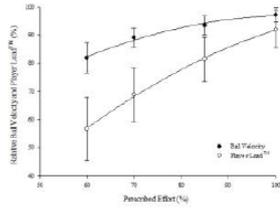
Microtechnology and Fast Bowling Intensity

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Peak Accelerometer resultant %	Mean 57.0% CV(%) 21.0 (19.0–24.0)	Mean 72.2% CV(%) 17.0 (15.0–19.0)	Mean 81.0% CV(%) 12.0 (10.0–13.0)	Mean 86.4% CV(%) 12.0 (10.0–13.0)
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Coefficient of variation (CV%) and 90% confidence interval.

Greater variability exists at lower intensities of bowling

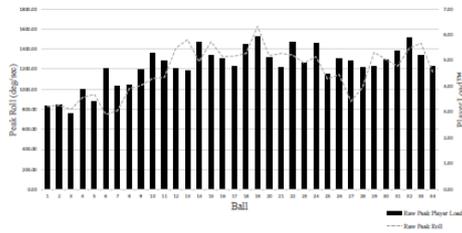
Microtechnology and Fast Bowling Intensity



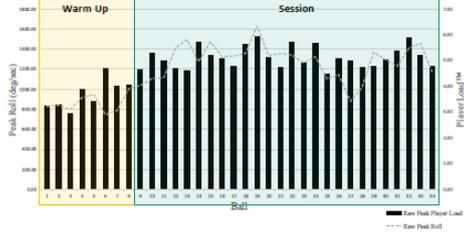
Meaningfulness of a Bowling Load



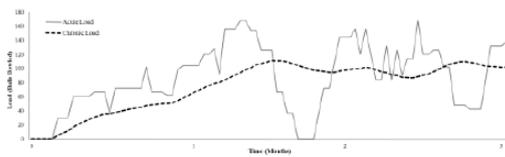
Meaningfulness of a Bowling Load



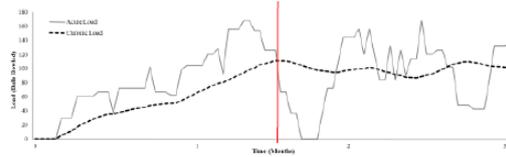
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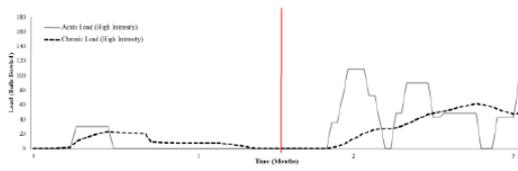
A Refined Acute/Chronic Ratio: Accounting for Intensity for an Individual Bowler during a Preseason



A Refined Acute/Chronic Ratio: Accounting for Intensity for an Individual Bowler during a Preseason



A Refined Acute/Chronic Ratio: Accounting for Intensity for an Individual Bowler during a Preseason



Consideration of bowling intensity needs to be considered in acute and chronic load relationships

In Summary

- Bowling detection algorithm from wearable microtechnology devices was sensitive to detect bowling counts in both cricket training and competition
- Refinements are required to account for false positives during competition

In Summary

- Metrics of bowling intensity may be able to be extracted from wearable microtechnology
- Consideration of **fast bowling intensity** is required when observing the acute/chronic workload ratio.

Cricket Australia Working Groups Conference. May 2016. Brisbane, AUSTRALIA

The application of wearable microtechnology/GPS in Cricket

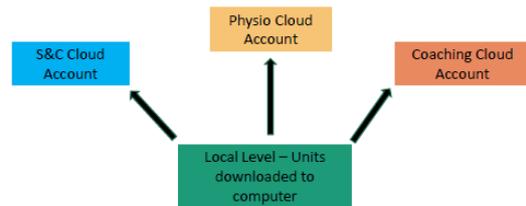
Dean McNamara

Presentation

1. Application of OpenField to Physiotherapy
2. Examples of Data from 2015/16
3. Measuring Bowling Intensity

Application of OpenField to Physiotherapy

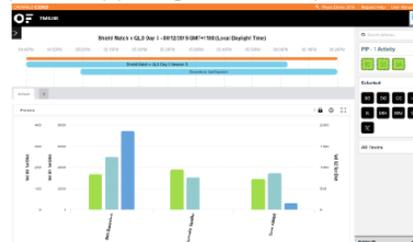
Physiotherapy Integration into OpenField



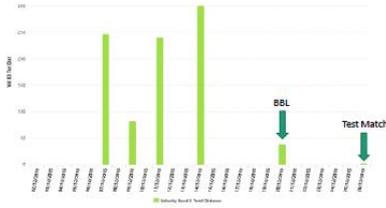
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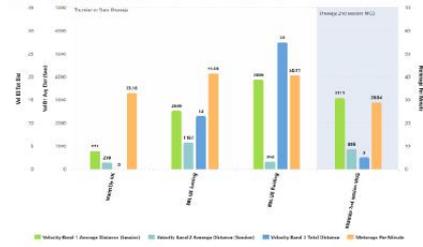
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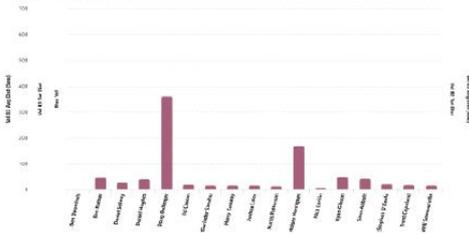
Hamstring Return to Play – High Speed Running Load



BBL Hundred vs Test Hundred



The Outliers



Measuring Bowling Intensity

Automated Bowling Counts via Wearable Microtechnology

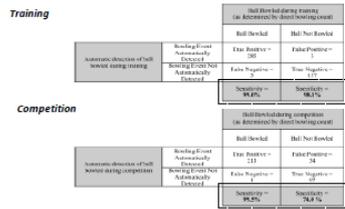


Automated Bowling Counts via Wearable Microtechnology

		Ball Bowled during Training (as Determined by Video/Recording)	
		Ball Bowled	Ball Not Bowled
Training	Automatic detection of ball bowled during training	Ball Bowled = 200	Ball Not Bowled = 1
	Bowling Error Admissibility	False Positive = 0	False Negative = 1
	Ball Bowled during competition (as Determined by Video/Recording)	Ball Bowled = 200	Ball Not Bowled = 1
Competition	Automatic detection of ball bowled during competition	Ball Bowled = 213	Ball Not Bowled = 54
	Bowling Error Admissibility	False Positive = 4	False Negative = 10
	Ball Bowled during training (as Determined by Video/Recording)	Ball Bowled = 200	Ball Not Bowled = 1

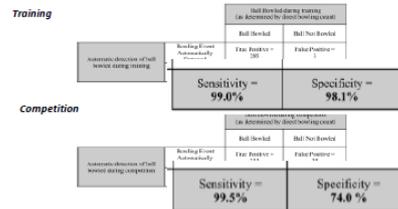
McNamara, et al, 2014

Automated Bowling Counts via Wearable Microtechnology



McNamara, et al, 2014

Automated Bowling Counts via Wearable Microtechnology

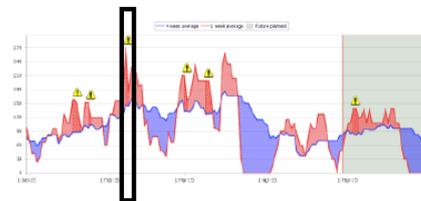


McNamara, et al, 2014

Significance of Automated Bowling Counts

- Automated measure of volume
- Easier to identify key variables of load
- Automated workload/intensity reports
- Enhanced ability to access data on across numerous sessions/seasons

Meaningfulness of a Bowling Load



Microtechnology and Fast Bowling Intensity

- Prescribed efforts of 60%, 70%, 85% & 100%
- Relative scores of
 - PlayerLoad™
 - Roll
 - Yaw
 - Resultant Accelerometer
- Ball Velocity



Microtechnology and Fast Bowling Intensity

Prescribed Effort Relationship	R	Ball Velocity Relationship	R
Resultant max %	0.71 ± 0.28 <i>Very Large</i>	Resultant max %	0.64 ± 0.33 <i>Large</i>
Player Load™ max %	0.83 ± 0.19 <i>Very Large</i>	Player Load™ max %	0.82 ± 0.20 <i>Very Large</i>
Roll max %	0.80 ± 0.21 <i>Very Large</i>	Roll max %	0.73 ± 0.27 <i>Very Large</i>
Yaw max %	0.56 ± 0.37 <i>Large</i>	Yaw max %	0.58 ± 0.36 <i>Large</i>

Polynomial regression ± 90% confidence intervals and descriptor.

Microtechnology and Fast Bowling Intensity

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Polynomial regression ± 90% confidence intervals and descriptor.

Microtechnology Outputs have very large relationships with bowling effort and ball velocity

Microtechnology and Fast Bowling Intensity

Variable	Bowling Intensity %			
	60%	70%	80%	100%
Peak Roll %	Mean 64.4% CV(%) 16.0 (14.0-18.0)	Mean 74.9% CV(%) 11.0 (10.0-13.0)	Mean 88.0% CV(%) 11.0 (9.3.0-12.0)	Mean 93.2% CV(%) 6.1 (5.4-7.1)
Peak Accelerometer resultant %	Mean 57.0% CV(%) 21.0 (19.0-24.0)	Mean 72.2% CV(%) 17.0 (15.0-19.0)	Mean 81.0% CV(%) 12.0 (10.0-13.0)	Mean 86.4% CV(%) 12.0 (10.0-13.0)
Peak Player Load™ %	Mean 55.7% CV(%) 19.0 (17.0-23.0)	Mean 68.8% CV(%) 14.0 (12.0-16.0)	Mean 81.4% CV(%) 9.6 (8.4-11.0)	Mean 92.1% CV(%) 7.3 (6.4-8.5)
Peak Yaw %	Mean 72.8% CV(%) 22.0 (19.0-26.0)	Mean 82.6% CV(%) 16.0 (14.0-18.0)	Mean 91.2% CV(%) 10.0 (9.1-12.0)	Mean 93.3% CV(%) 8.4 (7.4-9.7)
Relative Ball Velocity %	Mean 81.9% CV(%) 6.6 (5.8-7.7)	Mean 89.2% CV(%) 3.8 (3.4-4.4)	Mean 93.5% CV(%) 3.6 (3.2-4.2)	Mean 97.2% CV(%) 2.6 (2.3-3.0)

Coefficient of variation (CV%) and 90% confidence interval.

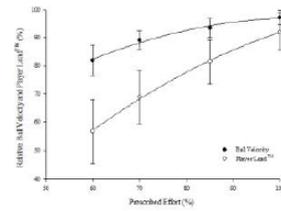
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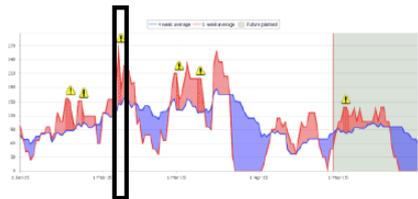
Coefficient of variation (CV%) and 90% confidence interval.

Greater variability exists at lower intensities of bowling

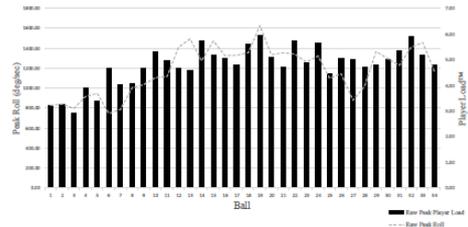
Microtechnology and Fast Bowling Intensity



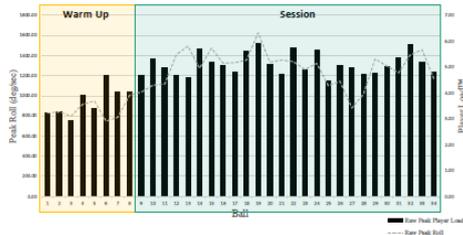
Meaningfulness of a Bowling Load



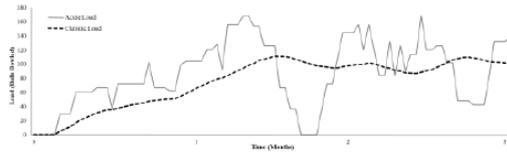
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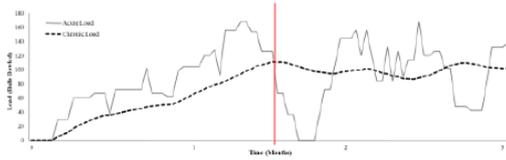
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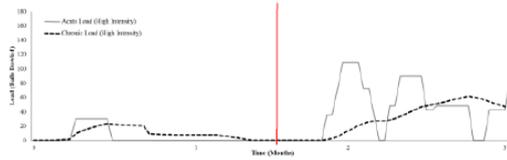
A Refined Acute/Chronic Ratio: Accounting for Intensity for an Individual Bowler during a Preseason



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A Refined Acute/Chronic Ratio: Accounting for Intensity for an Individual Bowler during a Preseason



Fast Bowling GPS/Microtechnology – Basic Outputs

Duration (mins)	Distance Band 1	Distance Band 2	Distance Band 3	Distance Band 4	Distance Band 5	PL	PL/min	Balls Bowled
84	2274	730	287	0	0	298.52	3.5475	31
84	2704	945	27	0	0	270.15	3.2107	33
84	2230	804	0	0	0	274.3	3.2006	40
248	10416.12577	1793.52998	110.14	0	0	917.98	3.6929	47
188	5946.91292	1391.91003	55.71	0	0	697.49	4.1301	44
188	5121.04014	874.89811	0	0	0	469.87	2.7851	56
122	4675.0498	1601.7298	11.88	0	0	439.75	3.5947	41
245	6440.45996	2883.57996	0	0	0	719.73	2.9317	84
25	1125.10597	698.97998	11.18	0	0	131.81	6.2076	29
169	6095.33008	1533.71997	60.18	0	0	633.81	3.7585	40
282	11462.83003	2348.72998	31.96	0	0	853.35	3.0056	72
317	11116.95972	3788.5	196.42001	0	0	1079.2	3.4046	109

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Fast Bowling GPS/Microtechnology – Bowling Data

N	O	P	Q
Balls/min	% H.I.		
1	0.37	81%	
3	0.39	55%	
0	0.48	0%	
7	0.19	68%	
4	0.26	0%	
5	0.33	18%	
1	0.34	46%	
4	0.34	100%	
9	1.16	10%	
0	0.24	80%	
2	0.26	60%	
9	0.34	58%	

High Intensity Balls	Band 2	Band 1	Ave
25			
18			
0			
32			
0			
10			
19			
84			
3			
32	1	7	
43	10	19	
63	38	8	

Fast Bowling GPS/Microtechnology – Bowling Data

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4	0.34	100%	
9	1.16	10%	
0	0.24	80%	
2	0.26	60%	
9	0.34	58%	

High Intensity Balls	Band 2	Band 1	Ave
25			
18			
0			
32			
0			
10			
19			
84			
3			
32	1	7	
43	10	19	
63	38	8	

In Summary

- Physiotherapy can interact on the OpenField cloud
- Wearable technology is providing meaningful objective data for decision making
- Future changes to how we look at Acute/Chronic workloads

Sydney Strength and Conditioning Working Group. November, 2015. Sydney,

AUSTRALIA



Overview

- Challenges with cricket
- Acute:Chronic Workload Ratio
- Technology in Cricket
- Part 1. Automated Bowling Counts
- Part 2. A Measure of Intensity
- Practical Application
- Part 3. The Meaningfulness of Intensity



Challenges in Cricket

- Formats of competition
- Yearly phases are not consistent
- A lot of player movement
- Paucity in applied research



Acute:Chronic Workload Ratio

Definition for cricket:
Acute load = 7-day average
Chronic Load = 28-day average

Both Session-RPE and Bowling counts for fast bowlers are defined as load

Think of chronic load as fitness and acute load as fatigue.



Acute:Chronic Workload Ratio



Technology in Cricket



Part 1. Automated Bowling Counts

		Ball Bowled during training (as determined by direct bowling count)	
		Ball Bowled	Ball Not Bowled
Automatic detection of ball bowled during training	Bowling Event Automatically Detected	True Positive = 263	False Positive = 3
	Bowling Event Not Automatically Detected	False Negative = 3	True Negative = 127
		Sensitivity = 99.0%	Specificity = 98.1%

		Ball Bowled during competition (as determined by direct bowling count)	
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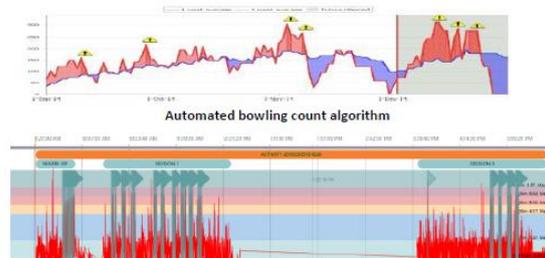
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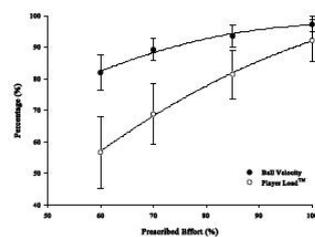


Part 2. A measure of intensity

- Participants included fast bowlers from the Cricket Australia High Performance Camp
- Bowlers were asked to bowl at 6x60%, 6x70%, 6x85% and 6x100%
- Measures of relative peak yaw, roll, PlayerLoad™, and resultant accelerometer were recorded for each ball.
- Ball velocity was recorded



Part 2. A measure of intensity



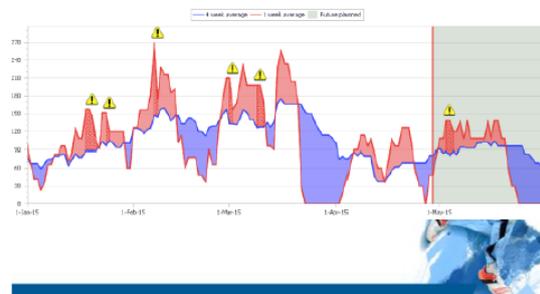
Part 2. A measure of intensity

Table 1. Relationship between bowling effort and microtechnology outputs

Prescribed Effort Relationship	R	Ball Velocity Relationship	R
Resultant max %	0.71 ± 0.28 Very Large	Resultant max %	0.64 ± 0.33 Large
Player Load TM max %	0.83 ± 0.19 Very Large	Player load max %	0.82 ± 0.2 Very Large
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Polynomial regression ± 90% confidence intervals and descriptor.

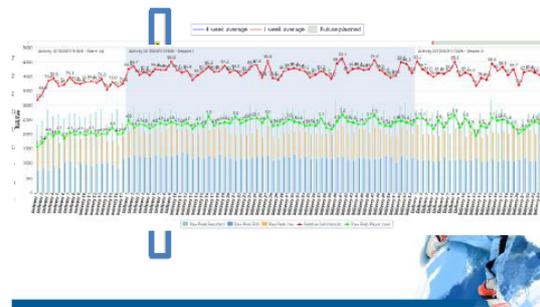
Practical Application



Practical Application

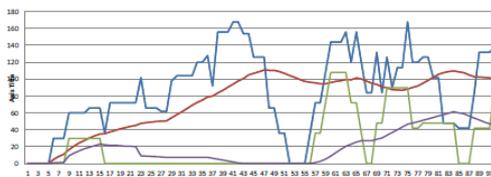


Practical Application



Part 3. The meaningfulness of intensity

AMS Ball Count - Acute vs. Chronic



Cricket Australia Working Groups Conference. May, 2015. Brisbane, AUSTRALIA



WORKLOAD – THE CRICKET PROBLEM

- Diverse
- Unique
- Evolving
- Somewhat Unknown



CRICKET AUSTRALIA

WHERE ARE OUR ASSETS?

Current Australian based contracted cricketers in non Australian competitions

Cricket Australia contracted = **60%**
NSW contracted = **32%**

Upcoming tours abroad:

- Male test team: West Indies and Ashes
- Australia A team
- Under 19s male tour
- Female Ashes tour

Monitoring systems need to be:

VALID | EASILY USED | VALUE ADD | SPECIFIC



CRICKET AUSTRALIA

GPS SYSTEMS IN AUSTRALIAN CRICKET

2013

- 60 units spread across Australian Cricket

Initial Goals:

- To familiarise and educate staff with the technology
- Players particularly fast bowlers comfortable wearing units at training
- Collect data

2014

- Look at training volumes across pre season comparatively between states
- Identify trends, training and games
- Begin to develop cricket specific systems



CRICKET AUSTRALIA

LIMITATIONS OVER PAST TWO YEARS

- Implementation
- Technical skill of users
- Interpretation by coaches
- Resources at a user level
- Player comfort
- Physical limitations – indoor training



CRICKET AUSTRALIA

WHAT WE KNOW SO FAR – A GENERAL SNAP SHOT

Volume	T20	50-Over	First Class	60m/min
Fast Bowlers	6km	12km	18-22km	30 - 35m/min
Batsman	4 - 4.5km	7 - 8km	10 - 20km	

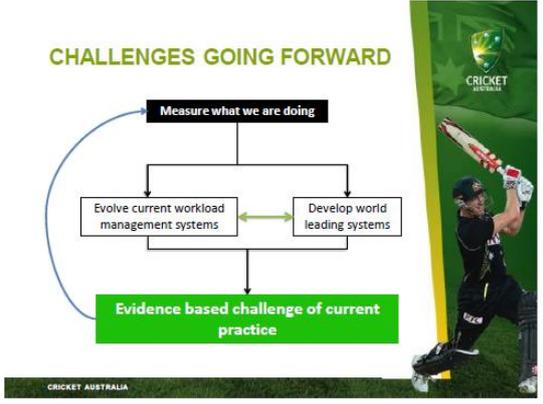
Intensity

- Batsmen reach velocities > 28km/h in matches
- Batsmen rarely reach velocities > 20km/h in training
- Fast bowlers reach velocities > 28km/h in matches
- Fast bowlers regularly reach velocities > 20km/h in training

Match intensity is not replicated at training, more apparent in batsmen



CRICKET AUSTRALIA



catapult.

THE SCIENCE OF WINNING
Track. Improve. Protect.

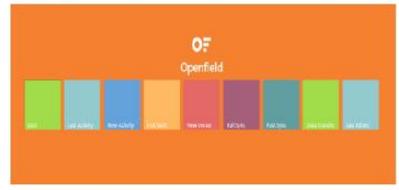


OUTLINE

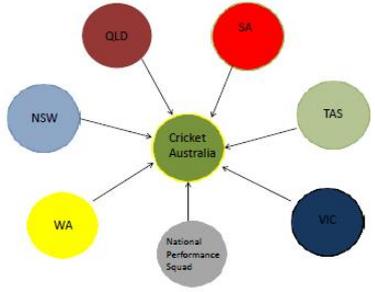
- OPENFIELD
- CRICKET AUSTRALIA AND OPENFIELD
- THE FUTURE

OPENFIELD

- Team Sport Software Platform



CRICKET AUSTRALIA AND OPENFIELD



CRICKET AUSTRALIA AND OPENFIELD

- Centralised Database
- Simplified Reporting Processes
- Bowling Algorithm
- http://au_beta.catapultsports.com



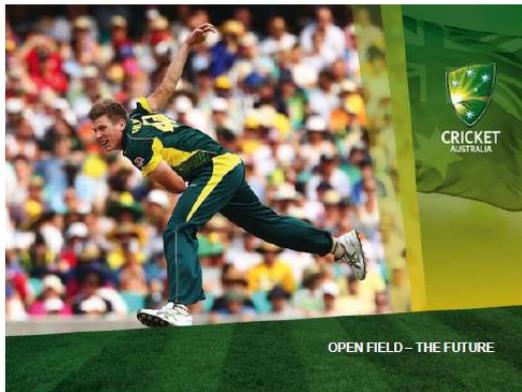
FUTURE

- Artificial Averages
- Improvements to the Bowling algorithm (reporting)



catapult.

THANK YOU FOR LISTENING



GPS IN TEAM SPORT

GPS is only one small piece of the puzzle



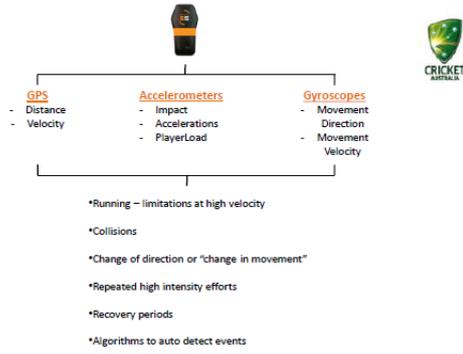
CRICKET AUSTRALIA



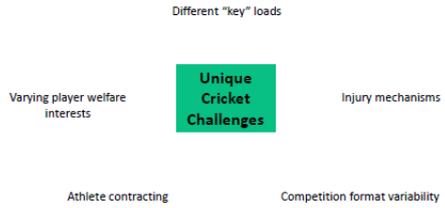
CRICKET AUSTRALIA



CRICKET AUSTRALIA



CRICKET VS OTHER TEAM SPORTS



CHALLENGES FOR USE IN CRICKET

Perceived Value Add	Limited Resources	Reduced Performance Predictor	Paucity in Research	Not “Cricket” Ready	Cricket “Not” Ready
Data not reflecting the needs of cricket performance	- State resourcing - Access to elite athletes to progress research	Not as strong as a predictor of performance comparatively	Very limited published research	Systems and reporting not meeting immediate needs	Poor understanding of “total load”: - Fielding - Competition type - Competition schedule - Ownership of athlete

KEY AREAS GOING FORWARD

- What are meaningful workload or physical events in cricket preparation and competition?
- Integrated and easily produced reporting
- Increase literature to link performance with workload events



INTEGRATION INTO CURRENT SYSTEMS – BOWLING COUNT

Training

		Ball Bowled during training (as determined by direct bowling count)	
		Ball Bowled	Ball Not Bowled
Automatic detection of ball bowled during training	Bowling Event Automatically Detected	True Positive = 285	False Positive = 3
	Bowling Event Not Automatically Detected	False Negative = 3	True Negative = 177
		Sensitivity = 99.8%	Specificity = 98.1%

Competition

		Ball Bowled during competition (as determined by direct bowling count)	
		Ball Bowled	Ball Not Bowled
Automatic detection of ball bowled during competition	Bowling Event Automatically Detected	True Positive = 211	False Positive = 38
	Bowling Event Not Automatically Detected	False Negative = 1	True Negative = 97
		Sensitivity = 99.5%	Specificity = 94.4%

McNamara, Gabbett, Chapman, et al 2014

INTEGRATION INTO CURRENT SYSTEMS – BOWLING COUNT

Training

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McNamara, Gabbett, Chapman, et al 2014

INTEGRATION INTO CURRENT SYSTEMS – BOWLING COUNT



Training



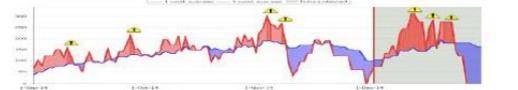
Competition



McNamara, Gabbett, Chapman, et al 2014

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INTEGRATION INTO CURRENT SYSTEMS – BOWLING COUNT



Automated bowling count algorithm



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INTEGRATION INTO CURRENT SYSTEMS – TAKING BOWLING COUNTS A STEP FURTHER



Needs analysis for project

- The need to address a broad definition
- Improve decision making from abroad
- Provide feedback in rehab bowling settings
- Gain insight into training intensity, match intensity and between competition intensity



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INTEGRATION INTO CURRENT SYSTEMS – TAKING BOWLING COUNTS A STEP FURTHER



- Participants included fast bowlers from the Cricket Australia High Performance Camp
- Bowlers were asked to bowl at 6x60%, 6x70%, 6x85% and 6x100%
- Measures of relative peak yaw, roll, PlayerLoad™, and resultant accelerometer were recorded for each ball. "MinimaxX Effort" were calculated
- Ball velocity was recorded



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INTEGRATION INTO CURRENT SYSTEMS – TAKING BOWLING COUNTS A STEP FURTHER

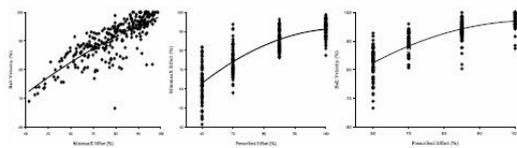


Prescribed Effort Relationship	R ²	Relative Ball Velocity Relationship	R ²
MinimaxX effort	0.73	MinimaxX effort	0.67
Resultant max %	0.50	Resultant max %	0.42
PlayerLoad™ max %	0.69	Player load max %	0.69
Roll max %	0.64	Roll max %	0.56
Yaw max %	0.32	Yaw max %	0.32

McNamara, Gabbett, Blanch and Kelly, 2015 (unpublished)

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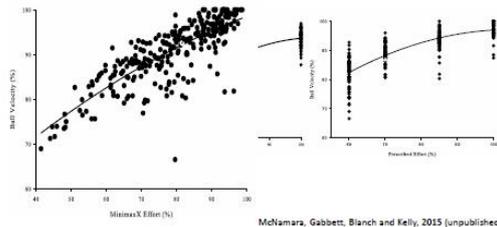
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McNamara, Gabbett, Blanch and Kelly, 2015 (unpublished)

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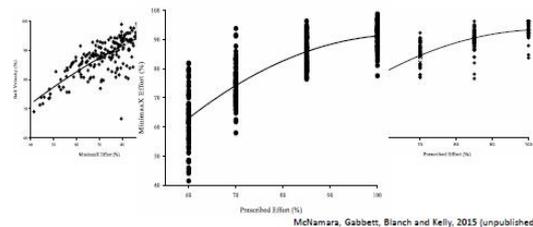
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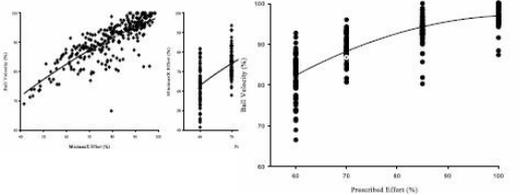
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McNamara, Gabbett, Blanch and Kelly, 2015 (unpublished)

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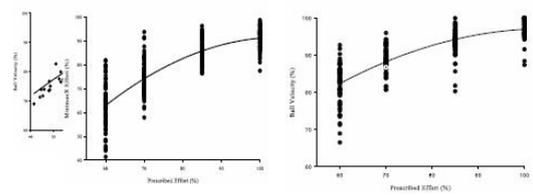
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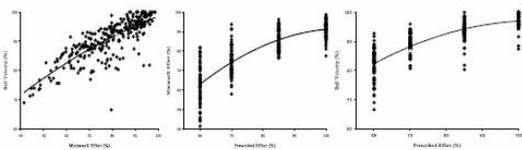
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McNamara, Gabbett, Blanch and Kelly, 2015 (unpublished)

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INTEGRATION INTO CURRENT SYSTEMS – TAKING BOWLING COUNTS A STEP FURTHER

How does this work in the day to day management of our fast bowlers?



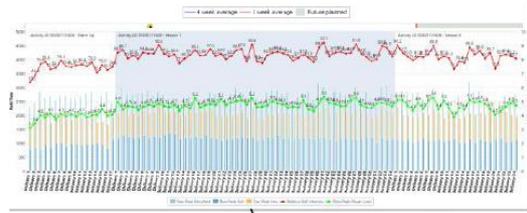
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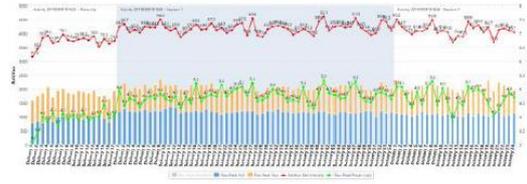
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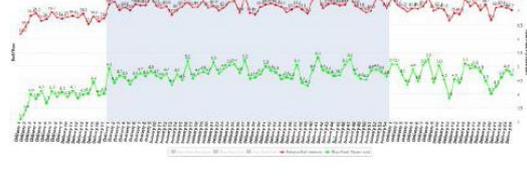
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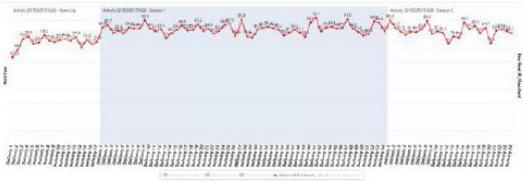
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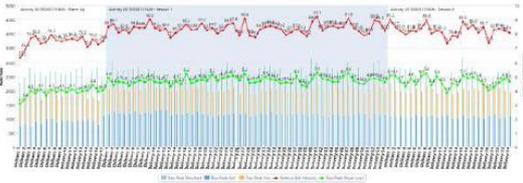


Practical use:

- Intensity bands for bowling
- Run up intensity not analysed in this data
- Easily produced reports

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INTEGRATION INTO CURRENT SYSTEMS – TAKING BOWLING COUNTS A STEP FURTHER



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INTEGRATION INTO CURRENT SYSTEMS – TAKING BOWLING COUNTS A STEP FURTHER

A work in progress

- Session analysis vs. career analysis
- Career analysis is the key:
 - Rehab
 - Decisions abroad
 - Training vs. competition
 - Competition vs. competition



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READY TO GO

Current uses of GPS systems that can be intergrated in player management.



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IMPROVED PREDICTION OF LOAD

Profile fielding and conditioning sessions

- Loads in each of the coaches sessions:
Max velocity, distance, RHIE, velocity bands, Player Load, RPE
- Integrated decision making regarding conditioning and skills training within weekly planning
 - Buy in from coaching staff
 - Conditioning games (e.g. max velocity in games)
 - Rehab decision making (exclusion/inclusion criteria)



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REHAB SETTING

Set bench marks in return to play:

Competition Requirements = X velocity, Y RHIE, Z distance, and V PlayerLoad

Data from the unit can add insight into the whole story:

- Rehab running protocols
- Measure in traditionally non timed events e.g. running between wickets in a net session
- Unstructured and/or reactive based sessions e.g. fielding sessions
 - Observe data from the entire session: Does the athlete participate as per their normal intensity?
 - Set thresholds: running velocity, work/rest ratios, distance, event duration – *scope for live data*



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INSIGHT INTO WOMEN'S CRICKET

Match play demands between competition types. Female and male competition

	Female		P
	50-over Cricket	20-over Cricket	
Female Slow (%)	83.4 ± 5.1	75.6 ± 8.4	0.01
Female Fast (%)	16.3 ± 5.1	24.0 ± 8.3	0.02
Female Sprint (%)	0.2 ± 0.2	0.3 ± 0.4	0.48
Distance (m)	8993.8 ± 2210.1	4998.4 ± 1595.5	<0.001
	Male		
Male Slow (%)	80.5 ± 5.6	80.2 ± 6.2	0.91
Male Fast (%)	18.9 ± 5.3	19.3 ± 5.9	0.84
Male Sprint (%)	0.6 ± 0.6	0.3 ± 0.7	0.24
Distance (m)	11163.8 ± 2463.5	5999.5	<0.001

Data reported as mean ± SD. P = One-way ANOVA.

Note: modified velocity bands for female population

McNamara, 2015 (unpublished)



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FINAL SAY

Cricket Australia GPS program in Openfield

- Short term rollout
- Long term rollout
- Consistent parameter bands across Australia
- Parameter input from all states
- R&D "shared"

Data storage

- Uploaded into Openfield cloud
- Cricket Australia access

The wearing of this technology will become the "norm"

Stepping stone into future technology

Monitoring abroad – future direction and challenges that face cricket



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QUESTIONS



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