Risk factors for repetitive microtrauma injury to adolescent and adult cricket fast bowlers

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Originality statement

I hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, or substantial proportions of material which have been accepted for the award of any other degree or diploma at UNSW or any other educational institution, except where due acknowledgement is made in the thesis. Any contribution made to the research by others, with whom I have worked at UNSW or elsewhere, is explicitly acknowledged in the thesis. I also declare that the intellectual content of this thesis is the product of my own work, except to the extent that assistance from others in the project's design and conception or in style, presentation and linguistic expression is acknowledged.

Signed ______________________________ Date ________________

Rebecca Jane Dennis

Abstract

Cricket is one of Australia's most popular sports, both in terms of participation rates and spectator interest. However, as with all sports, participation in cricket can be associated with a risk of injury. Injury surveillance in Australia and internationally has consistently identified fast bowlers as the players at the greatest risk of injury. This clearly establishes fast bowlers as the priority group for continued risk factor research.

The primary aim of this thesis is to describe the epidemiology of repetitive microtrauma injuries and identify the risk factors for these injuries to male adolescent and adult fast bowlers. The program of research consists of three sequential prospective cohort studies, which were conducted over four cricket seasons. The rate of injury was high in all these studies, with nearly half of the 305 bowlers sustaining an injury.

The first of the three studies, which was conducted over three seasons, recruited 95 adult first-class fast bowlers and investigated bowling workload as a risk factor for injury. The findings suggested that there were thresholds for both low and high workload, beyond which the risk of injury increased. The second study recruited 47 adolescent high performance fast bowlers for one season, and identified a significant association between high bowling workload and injury. Based on the results of these two studies, workload guidelines for adult and adolescent fast bowlers are described in detail in this thesis.

The third study expanded on the first two workload studies and concurrently investigated a range of potential injury risk factors relating to bowling workload,

physical characteristics and bowling technique. A total of 91 adult and adolescent high performance fast bowlers participated in the third study for one season. Two independent predictors of injury were identified: increased hip internal rotation and reduced ankle dorsiflexion.

This program of research has provided information that is essential for the development of evidence-based injury prevention guidelines for adolescent and adult fast bowlers. The next stage in the injury prevention process is to implement measures that control the exposure to the injury risk factors identified in this thesis.

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“Cricket to us was more than play,

It was a worship in the summer sun”

Edmund Blunden from “Pride of the Village”

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List of cricket terms

The language of cricket can be idiosyncratic and, for those not familiar with the game, difficult to interpret. The following list of terms defines some of the cricket-specific words and phrases used in this thesis. Those terms marked with an asterisk (*) have been defined by the author of this thesis. The remaining terms are defined by a dictionary of cricket [1], unless otherwise indicated.

- All-rounder – a player skilled in both batting and bowling or in both batting and wicket-keeping.
- Ashes – the title held by the current champions in the continuing competition between the national cricket teams of Australia and England.
- Back foot impact (BFI) * - the first point in time when the back foot is in full contact with the ground during the delivery stride. If the heel does not contact the ground in back foot landing, BFI is defined as the frame in the video footage that the movement of the foot about the toe has completed. If the movement of the foot about the toe continues throughout the back foot landing, BFI is defined as the frame in the video footage during which the foot is most stable and is bearing the greatest load, prior to the bowler pushing off the toe of the back foot.
- Bail – either of the two pieces of turned wood that are laid across the top of a set of stumps to form a wicket.
- Ball – the round ball is made of hard cork and string and covered in leather [2]. The ball is joined in two hemispheres by a seam, with slightly raised

stitching. The circumference of the ball is between 224mm and 229mm and weighs between 156g and 163g. For day matches, the ball is red. For day-night matches the ball is white, as it is easier in a game played under artificial lighting.

- Bat – the implement with which the batsman strikes the ball, consisting of a hitting part (blade) with a flat face and convex back, attached to a long cylindrical handle. The blade of the bat is made of willow and has a maximum width of 108mm. The maximum length of the bat is 965mm. Aluminium bats are banned [2].

- Batsman – either of the two players currently at the wicket; the striker or non-striker.

- Boundary – the limits of the playing area, marked by a line, fence or rope.

- Bowl – 1) to propel the ball in the direction of the striker's wicket by any fair and legal method of delivery; 2) to dismiss a batsman by hitting his wicket so that one or both of the bails is dislodged.

- Bowler – the player who bowls the ball at the striker's wicket; a player who specialises in bowling.

- Bowling crease – a line marked on the ground at each end of the pitch, from which the bowler delivers the ball. The bowling crease is in line with the stumps and extends on either side of them to reach a total length of 2.64m.

- Bowling machine – any of various mechanical devices designed to propel the ball towards the wicket in order to provide batting practice.

- Bowling workload * - the volume and frequency of bowling completed, as measured by the number of deliveries bowled per day, the number of deliveries bowled per week, the number of days between bowling occurrences, and the number of bowling days per week.

- Catch – to take and keep hold of the ball after it has been hit by the batsman and before it has made contact with the ground.

- Crease – any of the lines marked on the ground at either end of the pitch that are used to indicate the limits of a batsman's ground or the area in which a bowler may fairly deliver the ball.

- Day-night match – a limited-overs game in which one innings is played in the afternoon and the other under floodlights at night.

- Deliver – to propel the ball towards the batsman, especially, to release the ball from the hand in bowling.

- Delivery stride * – the step from back foot impact to front foot impact.

- Dismiss – to get a batsman or batting side out.

- Extras – any runs that do not result, directly or indirectly, from a scoring stroke made by the striker during a match. The runs are credited to the batting side, but not to an individual batsman. The umpire signals an extra and it is recorded separately on the scorecard.

* Fast bowler * - a bowler for whom the wicketkeeper would normally stand back from the stumps, due to the increased speed of the ball when bowled. Generally a fast bowler is deemed to deliver the ball at a speed greater than 140km/h.

* Fast-medium bowler * - a bowler for whom the wicketkeeper would normally stand back from the stumps, due to the increased speed of the ball when bowled. Generally a fast bowler is deemed to deliver the ball at a speed from 120km/h to 140km/h.

* Fielder – any member of the side that is fielding, apart from the bowler and wicketkeeper.

* First-class – denoting cricket played at the highest level, as defined by the International Cricket Council. Cricket played in matches of three or more days' duration between two teams of eleven players. In Australia, the major domestic competition (Pura Cup, formerly known as the Sheffield Shield) and Test matches are considered first-class.

* Follow-on – an enforced second innings taken by a side immediately after its first innings, when its first innings total falls short of its opponents' score by a stipulated number of runs (eg. 200 runs in a match of five days or more).

* Front foot impact (FFI) * - the first point in time when the front foot is in full contact with the ground during the delivery stride.

* Innings – a division of a cricket match in which one of the two teams has its turn to bat.

- Length – the point at which the ball pitches, considered in terms of the distance down the wicket that it travels after leaving the bowler's hand.

- Limited-overs – denoting a type of cricket or a game of cricket played under regulations allowing each side-one innings of a stipulated number of overs (usually 50 overs).

- Line – the direction of the bowled ball's flight from wicket to wicket.

- Maiden – an over in which no runs are scored off the bat.

- No-ball – a delivery judged by the umpire to be unfair. One run is added as an 'extra' to the score of the batting side, so long as no runs are made in any other way, and the no-ball does not count as part of the over. The fairness of a delivery is assessed according to a wide variety of criteria, such as placement of the bowler's feet and movement of the bowler's arm.

- Non-striker – the batsman who is at the opposite end of the wicket from the player who is facing the bowling (the striker).

- One-day match – a game played under regulations designed to produce a result within a single day's play, involving one innings per side limited by a stipulated number of overs (usually 50 overs).

- One-day international match – a one-day match (as defined above) played between representative teams from any two of the eleven countries with one-day international status according to the International Cricket Council.

- Over – six fair deliveries bowled consecutively by one bowler from one end of the pitch. Overs are bowled alternately from each end of the pitch and no bowler may bowl two overs consecutively in the same innings. No-balls and wides do not count in the over.

- Pitch – 1) the area of ground between the two sets of stumps; 2) the point at which the ball first makes contact with the ground after being delivered by the bowler.

- Popping crease – a line marked on the ground at each end of the pitch, parallel with the bowling crease and 1.22m in front of the stumps. It marks the forward limit of the batman's ground. The popping crease at the non-striker's end is used to mark the forward limit of the bowler's territory in determining whether a delivery is fair, whereby the umpire must be satisfied that some part of the front foot was behind the popping crease.

- Run-up – the bowler's running approach to the wicket prior to delivering the ball.

- Session – any of the three periods of play that make up a full day's cricket at first-class level, separated by the intervals for lunch and tea.

- Shoulder counter-rotation - a measurement of shoulder alignment (a line joining the acromion processes) in the transverse plane, which is characterised by a rapid realignment of the shoulders from a front-on foot and shoulder orientation at back foot impact, to a more side-on position (i.e. away from the batsman) just prior to front foot impact during the delivery stride [3, 4]. It is calculated by subtracting the angle of the shoulders when they are most side-on (between back foot impact and front foot impact), from the angle of the shoulders at back foot impact.

- Spell – a period of bowling by a particular bowler, consisting of a number of overs bowled consecutively from one end of the pitch, allowing for another bowler operating from the other end in alternate overs.

- Striker – the batsman who is facing the bowling.

- Stump – one of the three upright wooden rods which, with the two bails laid across their tops, form one of the two wickets used in a game of cricket. The stumps are 71.1 cm high.

- Test match – an international cricket match played between representative teams from any two of the ten countries with full membership of the International Cricket Council. Test matches are played over 5 days, with 6 hours play per day. Each day's play is divided into 3 sessions of two hours each, with a 40 minute break between the first two sessions for lunch and a 20 minute tea break between the last two sessions. A short drinks break is taken once an hour or more often in very hot weather.

- Wicket – 1) either of the two targets at which the ball is bowled in cricket and which the batsman defends with his bat, each consisting of three stumps set in the ground and surmounted by two bails, the whole construction measuring 71.1 cm high by 22.86 cm wide. The two wickets are set up opposite and parallel to each other; 2) the area of ground between the two sets of stumps, measuring 20.12 m in length and 3.04 m in width; 3) the dismissal of a batsman credited to a bowler. A team's innings is complete when ten of its eleven wickets have fallen.

- Wicketkeeper – a specialist fielder who stands behind the batsman's wicket, whose job it is to stop and catch balls behind the striker. The wicketkeeper takes up his position either right up to the stumps or well back from it, according to the speed of the bowler.

List of abbreviations

- ABS Australian Bureau of Statistics
- AIS Australian Institute of Sport
- BFI back foot impact
- CA Cricket Australia (formerly known as the Australian Cricket Board)
- CI confidence interval
- CT computerised tomography
- EMG electromyography
- EMTP exertional medial tibial pain
- FFI front foot impact
- ICC intra-class correlation coefficient
- MRI magnetic resonance imaging
- MTSS medial tibial stress syndrome
- MTT modified Thomas test
- NPBP National Pace Bowling Program
- OR odds ratio
- OSICS Orchard Sports Injury Classification System

- RCT randomised controlled trial
- Ref reference
- ROM range of motion
- RR risk ratio
- SEM standard error of measurement
- SSJCA Sutherland Shire Junior Cricket Association
- TRIPP Translating Research into Injury Prevention Practice

An introduction to cricket

The first tangible reference to the game of cricket was made in 1478 when a game called ‘criquet’ was played in France. In 1646, the first recorded cricket match took place in England, with the first encounter between two English counties being played in 1709. As the game’s popularity increased, the need to make rules became apparent and in 1744 the first Laws of Cricket were formulated. By the close of the nineteenth century, cricket had spread from its English roots and was being played in many overseas countries, particularly those which were part of the British Empire. International cricket in the form of test matches began in 1877, when England and Australia competed for the first time at the Melbourne Cricket Ground. It was the same two teams that contested the first international limited-overs match, also at the Melbourne Cricket Ground, in 1971 [5].

Cricket is a bat and ball sport for two teams of eleven players each, with the object of the game being to score more runs that the opposing team. A match is divided into innings. During an innings, one team bats while the opposing team fields and attempts to bring the batting team’s innings to an end. The team which is batting aims to score as many runs as possible. The fielding team tries to limit the runs scored by the batting team, whilst also trying to get the batting players out, to complete their innings. The game is adjudicated by two umpires, who make all decisions on the field.

The teams are comprised of players that specialise in different areas of the game: some in batting, some in bowling and one player who acts as a wicketkeeper. Some players can be selected in the team for their abilities across all activities and are called all-rounders. A team usually consists of four to five specialist batsmen, four to five specialist bowlers, one specialist wicketkeeper and one to two all-rounders. However, the composition of the team depends on the type of match being played (one-day match or a longer match) and the strategy of each particular team.

Play takes place on a large grassed area, ranging in size from approximately 90m – 150m across [2]. The laws of cricket do not stipulate the overall size of the playing field. A rope or fence marks the limits of the playing area and is known as the boundary. In the centre of the field is the pitch, a carefully prepared rectangle of closely mown and rolled grass. At each end of the pitch three wooden poles are placed in the ground (stumps), with two crosspieces (bails) sitting across the top of the stumps. Each set of stumps is collectively known as a wicket and each set of stumps are placed 20.12m apart. The pitch is 3.04m wide and on the pitch a number of lines, called creases, are marked. These creases indicate where the bowler is permitted to place their feet when delivering the ball and where the batsmen must run to. They are used by the umpire to adjudicate the fairness of a delivery and whether a batsman scores a run or has been dismissed by the fielding side.

The order in which the teams bat is usually decided by a coin toss. All eleven players of the fielding team go out to field, while two players of the batting team go out to bat. One batsman will face the ball being bowled and is called the striker. The other batsman stands down the other end of the pitch and is called the non-striker. The remaining members of the batting team wait off the playing area for their turn to bat. The members of the fielding team spread out around the field, trying to stop the batsmen from scoring runs or to get the batsmen out. One member of the fielding team is the bowler. He takes the ball and stands behind the batsman who is the non-striker. The bowler then runs in and bowls the ball (using an overarm action with a straight arm) to the batsman at the other end of the pitch (the striker). There are two basic approaches to bowling: fast and spin. A fast bowler bowls the ball as fast as possible, whereas a spin bowler uses a wrist or finger motion to impart spin to the ball. A bowler usually specialises in one form of bowling.

The highly specialist fielder who acts as wicketkeeper, stands behind the batsman's stumps to gather deliveries from the bowler (whether the batsman has hit them or not) and balls thrown in from the fielders. The bowler attempts to dismiss (get out) the striker, which can be achieved by hitting the batsman's stumps, or causing the batsman to hit the ball into a fielder' s grasp before it bounces, or through a number of other complicated methods. There are ten different methods of getting a batsman out. The batsman attempts to defend his stumps with a bat and to score runs by striking the ball to the boundary of the playing area, or far enough from any fielders to allow the batsman to run to the other end of the pitch before the ball can be returned. The batsmen pass each other while running and when each has reached the opposite end of the pitch to where they are standing, one run is scored. If the ball is hit along the ground to the boundary of the playing area, four runs are scored. If the ball does not touch the ground before landing outside the boundary, six runs are scored. Runs are credited to the batsman who has actually hit the ball (the striker). The batsmen do not have to run unless they want to, it is common to hit the ball and elect not to run if it is likely that one of the batsmen will get out.

When one bowler has bowled six fair balls it is called an over. When a bowler has completed his over, another member of the fielding team is given the ball and bowls the next over from the alternate end of the pitch. While the bowlers change ends at the end of each over, the batsmen do not. There are always two batsmen on the field, each to take their turn facing the bowler as required.

When all but one of the batting team have been dismissed, the batting side's opportunity to score runs is closed, and the roles are reversed. Each opportunity to bat, either for a team or an individual is called an innings. In a one-day limited overs match, each innings usually lasts 50 overs. For longer matches, each side has two innings. To win these longer matches, a side has to not only dismiss the opposition team twice but to also score more runs than them. Sometimes the time allocated to the match (eg. five days for Test matches) is not enough time for a definite result, and the game ends in draw.

PART A INTRODUCTION

A1: Introduction and aims of the thesis

A1.1 Sports injury as a public health issue

Injury was first recognised as a national health priority in 1986 [6]. It is a significant health issue in Australia, which caused 7,820 deaths (6% of all registered deaths) in 2002 [7]. Injury has consistently been recognised as the leading cause of death for people aged 1 – 44 years, being responsible for approximately 50% of deaths in this age group each year [6-8]. It was the fourth highest health expenditure area in Australia in 2000-01, as it accounted for 8% ($4.1 billion) of the total allocated health expenditure [9]. Although injury is one of the leading causes of mortality and morbidity in Australia, it is possible to reduce the burden of injury. This is because injury is not a random event, but a result of interaction between several factors (the person, the activity being undertaken and the immediate environment) and can be prevented and controlled by implementing effective prevention strategies [6, 10].

Within the area of injury prevention and control, sports injury has been recognised as being a considerable issue by government agencies. It was one of the ten priorities chosen for the development of national goals and targets for injury prevention and control, as it was significant in terms of mortality and morbidity and there appeared to be good opportunities for action to reduce injury rates in the short or long term [10, 11].

Although sports injury has been identified as a priority area in many government reports, there is limited information on the incidence of sports injury at the broad community level in Australia [12]. An early estimate was that one in 17 Australians suffer from a sports injury each year [13]. More recent calculations have stated that sports injuries cost more than $1.83 billion annually [14]. These estimates demonstrate that sports injury is a significant public health issue.

The incidence of sports injuries is a function of the high levels of participation, with many Australians taking part in sporting activities. An Australian Bureau of Statistics (ABS) General Social survey, for which information was gathered by personal interview, found that nearly two-thirds of Australians aged 18 years and over had participated in sports and physical activities in the 12 months prior to interview in 2002 [15]. Participation in sport is encouraged by government agencies and physical activity experts, based on research findings that participation provides health, physical, mental, social and economic benefits to the individual and the community [16-18]. However, an increased level of participation in sport increases exposure to the risk factors associated with sports injuries [19]. Although there are inherent risks in most sporting activities, like all other injuries sports injuries can be prevented or controlled through implementing appropriate interventions [12].

Although it has been acknowledged that many injuries can be prevented, the main focus of the health and funding sectors has been on treatment of sports injury, rather than prevention [12]. A recent overview of epidemiological studies in Australia concluded that whilst this research has started to provide evidence for potential sports injury risk factors, much still remains to be done [20]. It has been acknowledged in a number of papers that for sports injury prevention to progress, there is a need to combine a number of disciplines, including epidemiological, biomechanical and medical approaches [20-25].

As identified in a recent review report, there has been a significant increase in knowledge in some aspects of sports injury and sports safety over the past decade, whilst some remain quite limited [20]. A number of studies have documented the incidence of injury and risk factors for injury in a range of sports in Australia, including rugby league, rugby union, Australian rules football, basketball and hockey. However, cricket has not been widely researched in Australia, even though it has been identified by emergency department surveillance systems as being amongst the top 10 activities most commonly leading to a sports injury [26, 27].

A1.2 Cricket injury

Cricket is one of Australia's most popular sports, both in terms of participation rates and spectator interest. The Australian national cricket census, conducted by each of the six state and two territory cricket associations, reported that there were 410,919 participants in formal Australian cricket competitions and programs in 2003-04 [28]. A population-based survey of people aged 18 years and over reported that over 500,000 Australians participated in cricket (organised and/or non-organised activities) in the 12 months prior to interview in 2002 [15]. In this survey, cricket was identified as the 6th most popular activity for males [15].

As is the case with all sport and recreation activities, participation in cricket can be associated with a risk of injury. Until recently, hospital emergency department surveillance systems have provided most of the data on cricket injuries in Australia [26, 27]. The hospital emergency department surveillance system data indicates that cricket is among one of the most frequent sports leading to an emergency department attendance in Australia, however the information is limited because it does not take into account the numbers of people participating in the sport or the amount of cricket they played. It is therefore possible that the high numbers of emergency department presentations may merely reflect the popularity of cricket as a participant sport, rather than it being particularly hazardous. Even so, cricket-specific research has documented the incidence of injury among elite players in Australia and has also found that injury is relatively common [29].

Fast and fast-medium bowlers (hereafter collectively referred to as fast bowlers) have consistently been identified as being at the greatest risk of injury in both Australian [29] and international research [30-35]. The problem of injury to fast bowlers has been highlighted through injury surveillance at the elite level in Australia, with the injury prevalence (percentage of players unavailable for selection for a match at any given time) being 16% for fast bowlers, 4% for spin bowlers, 4% for batsmen and 1% for wicket keepers [36]. This clearly establishes fast bowlers as the priority group for further research to identify risk factors for injury.

Australian biomechanical studies conducted in the 1980’s and 1990’s identified bony and soft tissue injuries to the lower back as key areas of concern for fast bowlers [37-42]. These studies contributed greatly to understanding the role of bowling technique in the aetiology of these back injuries to fast bowlers, demonstrating that injuries to the lower back occurred more frequently amongst bowlers who adopted a mixed bowling technique, as compared with those using a front-on or side-on technique [37-42]. It has been proposed that injury to fast bowlers can be attributed to a combination of poor technique, poor physical preparation and overuse (in terms of bowling workload) [38, 40, 42]. In addition to the biomechanical studies of bowling technique, some studies have provided information about the role of the physical characteristics of fast bowlers [40, 42-45] and bowling workload [42, 46, 47] in the occurrence of injury.

A limitation of much of the cricket research conducted to date is the use of cross-sectional and retrospective study designs, which means that it is difficult to establish cause-effect relationships between the risk factors and injury. Whilst previous studies have helped identify the technique, physical characteristics and workload factors related to injury to fast bowlers, it is essential that continued prospective research builds on this information and develops a further understanding of the injury risk factors for both adolescent and adult fast bowlers.

Another limitation of some risk factor studies reported in the literature is that they have used specialised equipment and facilities to test fast bowlers, and the degree to which the testing procedures can be adopted in the cricket “real world” is unclear. It is important that reliable field-based screening protocols are developed so that cricket coaches and medical staff are able to easily and inexpensively monitor fast bowlers on an ongoing basis.

The importance of further research into the risk factors and mechanisms of injury to fast bowlers has been identified by several researchers [48, 49], as well as by coaches and administrators of the sport. Most recently, the Chief Executive Officer of Cricket Australia stated that “it is critical that we examine the root causes of fast bowler injuries and work towards nullifying them as soon as possible” [50]. Continued prospective research will contribute to providing a solid evidence base for injury prevention strategies for fast bowlers.

A1.3 Aims of the thesis

The primary aim of this thesis is to describe the epidemiology of repetitive microtrauma injuries (those injuries associated with repetitive microtrauma of the musculoskeletal system attributable to fast bowling) and to identify the risk factors for these injuries to adolescent and adult cricket fast bowlers. The specific research questions to be answered are:

- What is the frequency of repetitive microtrauma injury among fast bowlers in a season?
- What is the bowling workload of fast bowlers during a season and how does this relate to injury occurrence?
- What are the physical characteristics of fast bowlers and how does this relate to injury occurrence?
- What are the characteristics of bowling techniques used by fast bowlers and how does this relate to injury occurrence?

- What are the intrinsic and extrinsic risk factors for cumulative microtrauma injury to fast bowlers?

The approach taken in this program of research is primarily epidemiological. However, as suggested in several research papers and government reports, there is a need to combine a number of approaches, including epidemiological, biomechanical and medical, for sports injury prevention to progress [20-24, 51]. For this reason, the epidemiological research described in this thesis has incorporated some concepts and frameworks provided by other sports injury disciplines.

A1.4 Structure of the thesis

This thesis describes a series of staged activities, which were conducted over four consecutive cricket seasons. The structure of this thesis is as follows:

- Part A presents the Introduction and Literature Review.

- Part B describes a series of three studies, which investigate risk factors for repetitive microtrauma injury. Each chapter (B1, B2 and B3) describes a specific stage of the overall program of research and includes introduction, methods and results sections.

- Part C focuses on the reliability of the screening protocols. Chapter C1 reviews a method for determining the inter- and intra-observer reliability of the screening protocols used in Part B. The results of these reliability assessments are described in Chapters C2, C3 and C4.

- Part D provides a detailed discussion of the results of the studies presented in Part B and the overall implications of the findings.

- Part E presents the conclusions and recommendations of the overall research program and describes potential future research directions.

- Part F lists the references used in this thesis.

- Part G lists the publications and presentations relating to the research presented in this thesis.

- Part H contains the appendices.

Part B of this thesis describes a series of three prospective cohort studies, which each recruited different groups of fast bowlers. The aims of each sequential study presented in Part B (sections B1, B2 and B3) are summarised below:

- B1 describes a study of 95 male first-class fast bowlers conducted over the 2000-01, 2001-02 and 2002-03 cricket seasons. The primary aim of this study is to describe the relationship between bowling workload and repetitive microtrauma injury. This research has already been published in a peer-reviewed journal (Dennis, R., Farhart, P., Goumas, C. and Orchard, J. (2003). Bowling workload and the risk of injury in elite cricket fast bowlers. Journal of Science and Medicine in Sport, 6(3), 359-367). A copy of the paper is attached as Appendix 1.

- B2 describes a study of 47 male adolescent high performance fast bowlers conducted over the 2002-03 cricket season. The primary aim of this study is to describe the relationship between bowling workload and repetitive microtrauma injury. This research has already been published in a peer-reviewed journal (Dennis, R.J., Finch, C.F. and Farhart, P.J. (2005). Is bowling workload a risk factor for injury to Australian junior cricket fast bowlers? *British Journal of Sports Medicine, 39*(11), 843-846). A copy of the paper is attached as Appendix 2.

- B3 describes a study of 91 male adolescent and adult high performance fast bowlers conducted over the 2003-04 cricket season. The primary aim of this study is to describe bowling workload, technique and physical characteristics as risk factors for repetitive microtrauma injury.

Finally, the design and aims of the reliability studies presented in Part C of this thesis are summarised below:

- C1 presents a review of a statistical method for determining the inter- and intra-observer reliability of the screening protocols used in B3. This has been submitted to a peer-reviewed journal and is currently being reviewed (Dennis, R.J., Hayen, A. and Finch, C.F. (2005). Determining the intra- and inter-observer reliability of screening tools used in sports injury research. *Journal of Science and Medicine in Sport,* (submitted)). A copy of the paper is attached as Appendix 3.

- C2 describes a reliability study of the musculoskeletal screening protocol with 10 participants conducted in 2004. The primary aim of this study is to describe the inter- and intra-observer reliability of the musculoskeletal screening protocol used in B3.

- C3 describes a reliability study of the fitness testing protocol with 10 participants conducted in 2005. The primary aim of this study is to describe the inter- and intra-observer reliability of the fitness testing protocol used in B3.

- C4 describes a reliability study of the technique analysis protocol with 10 participants conducted in 2005. The primary aim of this study is to describe the inter- and intra-observer reliability of the technique analysis protocol used in B3.

A2: Literature review

A2.1 Definition and categories of sports injuries

Biomechanically, a musculoskeletal injury can be considered to be a mechanical disruption of tissues [25]. However, in the sports injury literature, there is no common operational definition of ‘injury’. The definition of injury used in specific projects has varied according to the source of the injury data and the purpose of the injury surveillance [52]. Therefore, when comparing the results reported in sports injury studies (such as injury incidence rates), it is important to consider how the definition of injury used in each study has affected the results obtained. For example, a definition based on presentation to a hospital emergency department will include a greater proportion of acute injuries and fewer overuse injuries [53]. There are also major differences in the injury data collected for community-level participants and elite athletes if the definition of injury is based on criteria according to the consequences of the injury, or the treatment they receive for an injury. For example, elite athletes have increased access to medical support and may receive a greater amount of treatment for an injury, as compared with community-level participants.

Two broad categories of injury have been reported in the literature: ‘acute’ and ‘overuse’. Acute injuries occur suddenly and are associated with a single, macrotraumatic event . The inciting event, or mechanism of the injury, is usually clearly identified as being the application of some external force with resultant tissue disruption [12, 50]. Examples of acute injuries are fractures and ligament sprains. Acute injuries are also sometimes referred to as ‘sudden impact’ injuries.

The second broad category of injury is often referred to as ‘overuse’ injury in the literature. Other terms such as ‘gradual onset’, ‘chronic’, ‘idiopathic’ and ‘cumulative trauma’ have also been used. However, as argued by Gregory, ‘overuse’ implies the cause of the injury, and may also infer that simply ceasing participation in the activity of interest will resolve the problem [54]. Overuse injuries are the focus of the research program described in this thesis, but will be defined as ‘repetitive microtrauma’ injuries. These injuries develop gradually and are associated with repetitive microtrauma of the musculoskeletal system, where a number of repetitive forces, each lower than the critical limit of selected tissues, produce a combined fatigue effect over time and reduce the tolerance of the affected structures to load [50]. The inciting event is not as apparent, as compared to acute injuries, and the resultant tissue damage is more due to mechanical degradation than to acute disruption [55, 57]. Repetitive microtrauma injury may affect the structures of muscle, ligament, tendon, cartilage and bone [58]. Examples of repetitive microtrauma injuries are stress fractures and tendinitis.

Sometimes an acute injury is superimposed on a chronic mechanism . In these cases, cumulative loading leads to reduced tissue tolerance, which is then exceeded by short-term exposure to a high load [59]. Essentially, continued, repeated loading leads progressively to degenerative conditions that set the stage for an acute injury [50]. A muscle strain is an example of an acute injury being superimposed on a chronic mechanism [54]. More detail regarding the effects of repetitive microtrauma on the various tissues of the human body is provided in section 2.13 of this Literature Review.

In summary, the focus of this thesis is on the broad group of injuries which are commonly called ‘overuse’ injuries in the literature, including acute injuries with a chronic mechanism. In the program of research described in thesis, they are defined as ‘repetitive microtrauma’ injuries. However, when referring to specific publications in this Literature Review, the original terminology used to categorise and describe injury in those studies has been retained.

A2.2 Definition of sports injury risk factors

An understanding of the risk factors contributing to injury is the cornerstone of prevention [60]. A ‘risk factor’ for injury has been defined in a number of ways: a condition, object or situation that may be a potential source of harm for people [58]; and a measurable characteristic associated with a higher probability of injury [60]. Risk factors include characteristics that are risk markers or risk indicators, as well as characteristics that are determinants, or causes, of injury [50].

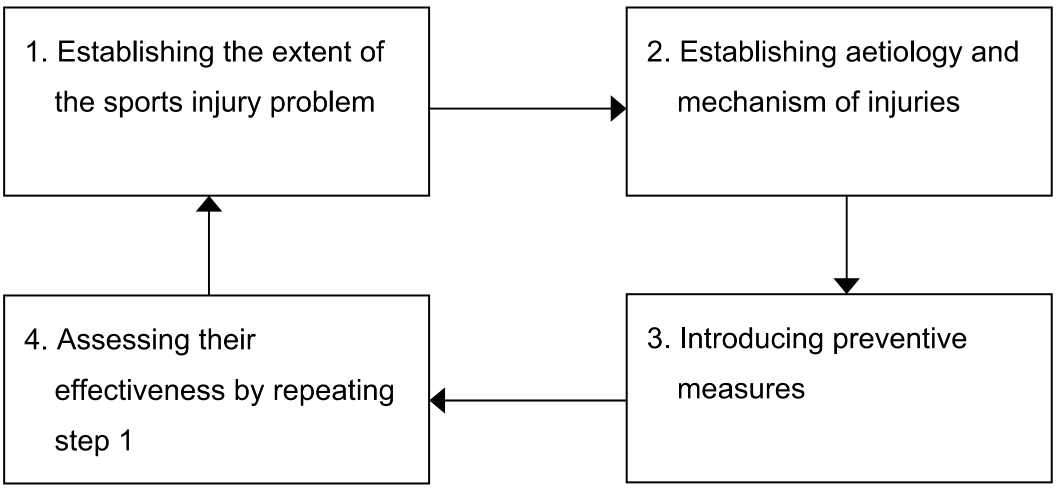
Risk factors for sports injury can be divided into two main categories [54, 61]. Intrinsic (internal, personal) risk factors include physical fitness, previous injury, physical build and age; whilst extrinsic (external, environmental) risk factors include protective equipment, weather conditions, type of sport and exposure within the sport [62]. Intrinsic and extrinsic injury risk factors can also be classified as being modifiable or non-modifiable [63]. As argued by Bahr and Holme [63], whilst non-modifiable factors such as age, gender and injury history may be considered, it is imperative that risk factor studies also investigate those factors that are potentially modifiable through interventions in physical training or behaviour, such as flexibility, strength and training volume.

A2.3 Models of sports injury prevention

The development of successful sports injury prevention strategies relies on a solid evidence base. Sports injury prevention can be considered a staged process and in this section, two conceptual frameworks for sports injury prevention are described. It is these frameworks that provide the theoretical underpinnings for the research program described in this thesis.

One of the first models to specifically address the issue of sports injury prevention was developed by van Mechelen and colleagues [64] and is illustrated in Figure 1. This four-stage model was based on basic risk management principles.

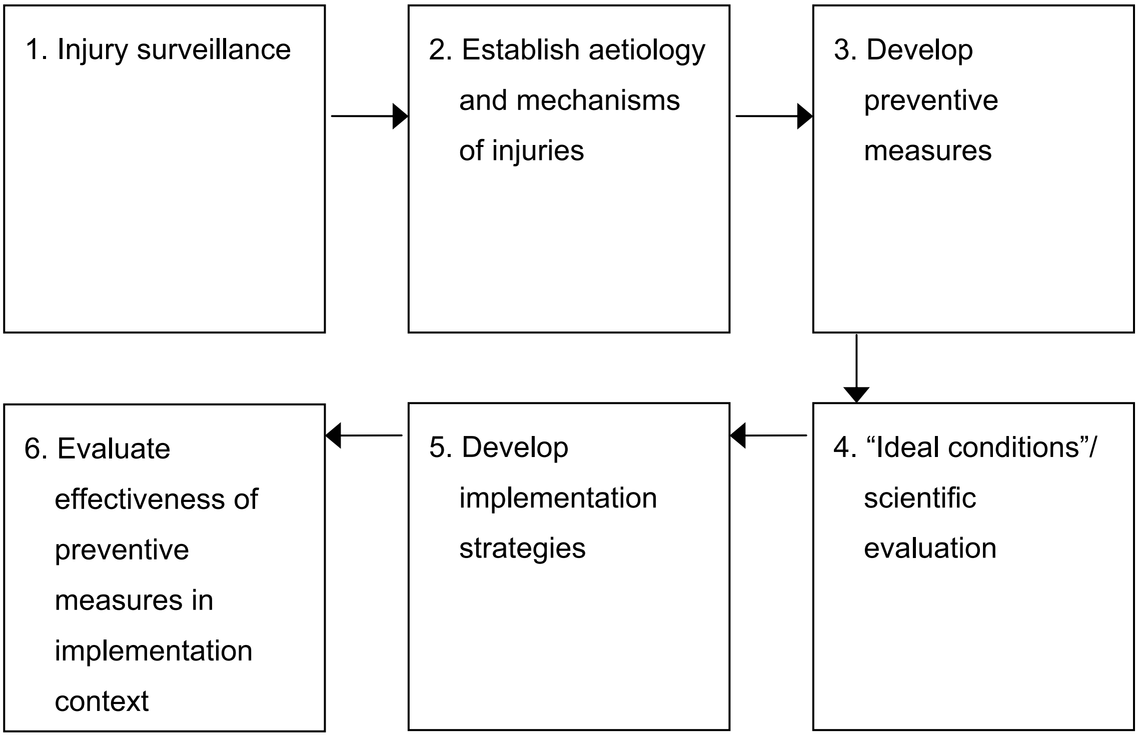
Figure 1 The four-stage sequence of prevention of sports injuries proposed by van Mechelen and colleagues [65]



As shown in Figure 1, the first stage of the process involves describing the extent of the injury problem through injury surveillance, typically using a measure of injury incidence. The second stage involves conducting epidemiological research to identify those factors that play a role in the occurrence of injury [64]. This includes collecting information about why particular athletes may be at risk in a given situation (injury risk factors, as described in section 2.2) and how injuries happen (injury mechanisms) [50]. To collect information about injury risk factors, it is necessary to refer to a conceptual model on the aetiology of sports injuries. Some of the models that have been developed to conceptualise the aetiology of injury are described in detail in section 2.4 of this Literature Review. The third stage of the 'sequence of prevention' involves the implementation of preventive measures (eg. personal protective equipment) and finally, assessing the effectiveness of this intervention by repeating the first stage of injury surveillance.

Recently, a new framework for sports injury prevention was proposed [50]. Finch suggested that there were a number of limitations to the four-stage model proposed by van Mechelen and colleagues, primarily being the lack of consideration for the implementation of research findings [66]. It was argued that only research that can, and will, be adopted by sports participants, coaches and sporting bodies, can prevent injuries [66]. To address this concern, Finch developed a new six-stage framework, called TRIPP (Translating Research into Injury Prevention Practice), which is illustrated in Figure 2.

Figure 2 The six-stage Translating Research into Injury Prevention Practice (TRIPP) framework for sports injury research developed by Finch [64]



The TRIPP framework differs from van Mechelen’s ‘sequence of prevention’ in a number of ways. The TRIPP model proposes that the preventive measures developed to address the identified mechanisms of injury should first be tested under controlled conditions to determine their efficacy. Following this, the interventions need to be considered for how they can actually be implemented in the sporting “real world”. This involves developing an understanding of the context in which the interventions will be implemented and modifying the interventions according to the requirements and behaviours of the participants, coaches and administering bodies [64]. Finch argued that only those research endeavours that adopt the six-stage TRIPP framework will result in injury prevention gains, as the framework ensures that the research findings can be translated into action by considering the “real world” context of the sport [64].

These two models have established conceptual frameworks for the development of successful sports injury prevention strategies and provide an overview of the “bigger picture” of the process of sports injury prevention. In comparison with the four-stage model [67], the additional stages of the six-stage TRIPP model [68] enable the translation of research findings into practice. It is beyond the scope of the research program described in this thesis to address all of the stages that contribute to the sports injury prevention process described in the six-stage TRIPP model. The focus of the research in this thesis is on establishing the injury problem among fast bowlers and establishing the aetiology of these injuries and thereby addresses the first and second stages of the injury prevention process. To some extent, it also suggests preventive measures, the third stage of the process. Continued research should use the six-stage TRIPP model to further develop the research described in this thesis and complete the injury prevention process.

A2.4 Models of sports injury aetiology

Injury prevention is the process by which the probability of injury is reduced by interventions aimed at addressing the risk factors for injury. But before injury prevention is possible, the relevant risk factors in the causal pathway need to be identified [68]. Models of sports injury aetiology help provide evidence for the aetiology and mechanisms of the injury, which is the second stage of the six-stage sports injury prevention process described by Finch [68].

The cause of sports injury is multifactorial and injury results from the interaction of a number of risk factors and events [68]. Injuries cannot often be attributed to the presence of a single extrinsic or intrinsic risk factor, but to combinations of these risk factors [68]. Also, whilst it is important to establish the intrinsic and extrinsic risk factors for injury, to develop an understanding of the causes of sports injury it is necessary to identify the mechanisms by which these injuries occur [68]. Bahr and Krosshaug have suggested that to understand the aetiology of sports injuries, researchers should not examine in isolation the intrinsic risk factors, extrinsic risk factors and the biomechanics associated with injury, but to use a model that accounts for all of these factors simultaneously [64].

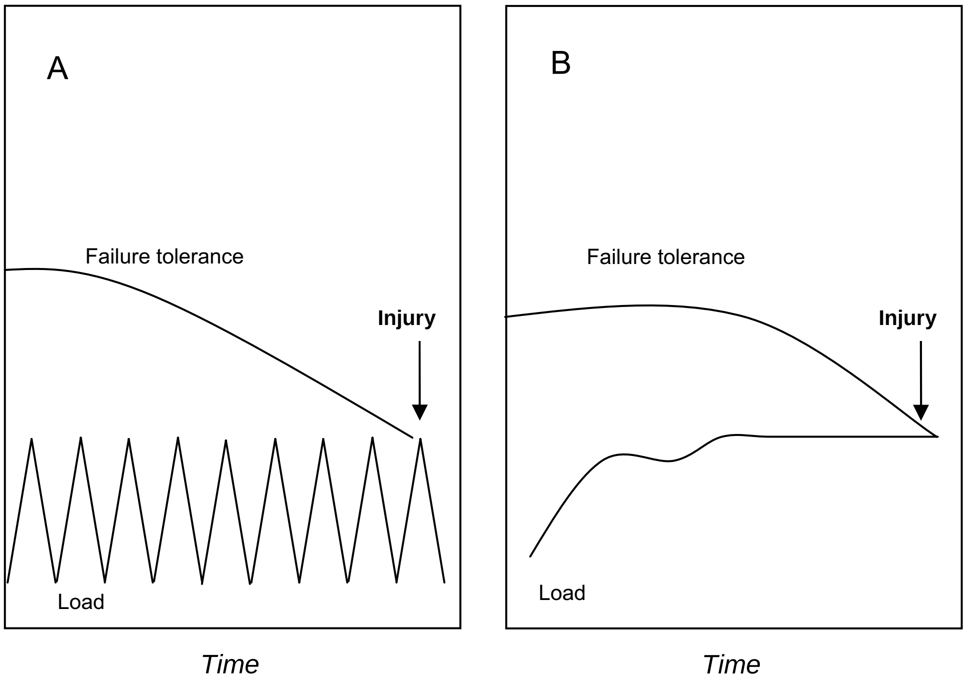
The majority of the specific research questions for the program of research described in this thesis focus on investigating the risk and aetiological factors associated with repetitive microtrauma injury to cricket fast bowlers. Models of sports injury aetiology provide the theroretical framework for addressing these research questions. Several models of sports injury aetiology have been described in the scientific literature, with these models evolving over time to incorporate and integrate a number of different perspectives.

Meeuwisse developed a multifactorial epidemiological model of sports injury aetiology, which allowed the investigation of the contribution of a number of single factors to the occurrence of injury, as well as the interrelationships between these factors [68]. In this model, it was suggested that an athlete may be predisposed to injury due to a number of intrinsic risk factors, such as age, strength, flexibility and skill level [69]. The predisposed athlete may then be subjected to a number of extrinsic risk factors, such as weather, playing surface type, protective equipment and opposition players, which facilitate the manifestation of injury. At this stage, due to the interaction between intrinsic and extrinsic risk factors, the athlete was considered as being susceptible to an injury occurring in a given situation. Meeuwisse stated that whilst the presence of the intrinsic and extrinsic risk factors meant that the athlete was susceptible to injury, they alone were not sufficient to produce an injury [68]. The final stage in the model was the inciting event that was considered the necessary cause of the actual injury [66].

In a recent paper proposing a biomechanically focused model of injury causation and prevention, McIntosh stated that injury results from a transfer of energy to the human tissue, the mechanical properties of which, (such as stiffness, ultimate strength and critical stress) determine how the body responds to physical loads [70]. These mechanical properties differ for each tissue and are dependent on the type and velocity of the load, the magnitude of energy transfer and intrinsic factors such as age, gender and physical condition; and it is the relationship between this load, and tolerance for the load, that decides the injury outcome of an event [66, 67].

In addressing the issue of tissue loading, McGill has proposed three types of tissue load that cause low back injury [54]. Two of these provide a theoretical understanding of tissue loading relating to repetitive microtrauma injuries to fast bowlers, which are the focus of this thesis. These two types of tissue loading are shown in Figure 3. In Figure 3A, injury is the result of accumulated trauma produced by either the repeated application of relatively low load or the application of a sustained load for a long duration. In Figure 3B, stress is induced over a sustained period of time, causing a progressive reduction in the tolerance of the tissue.

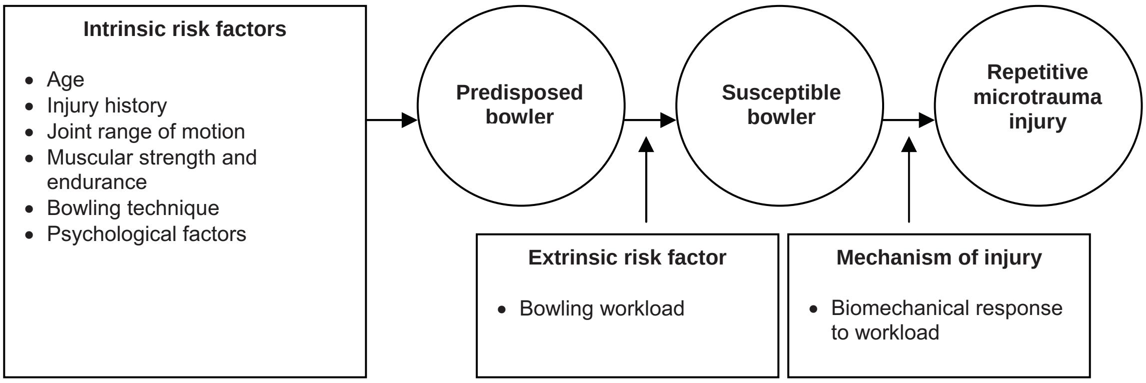
Figure 3 Two types of tissue load that lead to injury (adapted from McGill [54])



Biomechanical risk factors must explain how the event resulted in a mechanical load in excess of that tolerated under normal circumstances, or a reduction of the tolerance levels to a point at which a normal mechanical load could not be tolerated [54]. In this context, injury interventions should focus on modifying the loads applied externally and internally to the body; by either reducing the load below relevant injury tolerance criteria, or improving the body's capacity to tolerate certain patterns of loading [54]. The model of sports injury causation and prevention proposed by McIntosh incorporates a number of inputs including behaviour/attitudes, training, skills, equipment, coaching and the environment, with the output of injury risk. The model may be applicable to both single events and repeated events, in which micro and/or macro failure may occur [71].

Bahr and Krosshaug recently developed a new model for sports injury causation [71], expanding the model proposed by Meeuwisse [67], by incorporating the biomechanical perspective, as suggested by McIntosh [72]. This model acknowledges that injury occurs when an imposed load exceeds the tolerance (load-carrying ability) of a tissue, however it also considers that there are many other contributing factors that influence the relationship between load and repetitive microtrauma injury [72]. These include age [71], genetics [71], anatomical considerations [54, 67, 71], physiological factors [60, 71], nutrition [60] psychological factors [60, 61, 73], training schedule [60, 73, 74], technique [60], environment [60, 73], previous injury [61, 73] and rehabilitation [61]. In this model both intrinsic and extrinsic risk factors can affect load and load tolerance, which means that information on these risk factors, along with identification of the mechanism of injury, can be used to develop targeted injury prevention strategies that can modify injury risk [61, 74]. This model was adapted from the original model described by Bahr and Krosshaug [73], to reflect the focus of this thesis, repetitive microtrauma injury to fast bowlers. This adapted model is presented in Figure 4.

Figure 4 Model of injury causation for repetitive microtrauma injury to cricket fast bowlers (adapted from Bahr and Krosshaug [60])



As described by Krosshaug and colleagues, a number of different approaches have been used in the scientific literature to describe the inciting event, or mechanism, of various sports injuries [60]. These include interviews with injured athletes, clinical studies, analysis of video recordings of injury, in vivo studies, mathematical modelling and motion analysis of non-injury simulations [61]. Each approach has a number of strengths and weaknesses, and one approach alone may not provide sufficient information to describe the mechanism of injury. Therefore it is necessary to combine a number of different approaches that contribute a range of perspectives regarding the inciting event, or mechanism of injury [60].

A2.5 Identifying intrinsic risk factors for injury

Over recent years there has been an increasing call to provide a firm evidence base for sports injury prevention initiatives. As argued by Bahr and Krosshaug [67], provision of this evidence base is limited by knowledge about the aetiological factors causing many sports injuries. In the model of sports injury aetiology proposed by Bahr and Krosshaug outlined in section A2.4, one of the first stages of the process is to understand why an athlete may be predisposed to injury [75]. This requires conducting studies to identify the intrinsic risk factors for sports injury. Such studies involve the measurement of potential risk factors and relating these to injury outcomes.

Pre-participation (baseline) screening is a commonly used method for the collection of data relating to potential intrinsic risk factors [67], measuring factors such as flexibility, muscle strength and athletic technique [67]. The pre-participation screening is conducted to identify characteristics of the musculoskeletal system that may predispose an athlete to injury, or to identify incomplete recovery from a previous injury [75]. In a prospective study, measurements are made on participants in an injury-free state, eg. at the start of a playing season, and these are related to injury outcomes during the following participation period.

A major issue encountered by studies of intrinsic risk factors is a lack of reliability. The ability for studies to clearly identify potential risk factors is highly dependent on the accuracy with which these measurements are made [75]. So that the data collected during these pre-participation screenings can be used to identify injury risk factors and subsequently inform the development of effective injury prevention strategies, it is vital that the screening protocols are reliable [67, 75]. Measurements need to be reproducible over time and by different observers, as well as being repeatable within a given individual. Poor reproducibility limits the ability of researchers to reach conclusions about whether a measured variable is indeed a risk factor for injury, because it is difficult to differentiate participants with or without the variable of interest in the presence of large random measurement error [67]. Establishing reliability is a prerequisite for ascertaining the validity of the risk factor measures. As the program of research described in this thesis uses measurements of intrinsic risk factors to determine injury risk, a reliability assessment of the screening protocols was conducted, and is described in Part C.

A2.6 Epidemiological study designs

At the beginning of this Literature Review, the conceptual frameworks for sports injury prevention were described in section A2.3. These frameworks explain a staged process, with the collection of injury and risk factor data for the subsequent development of injury prevention initiatives. There are several epidemiological research designs that allow the investigation of the association between the proposed risk factors and injury, including cross-sectional studies, case-control studies, prospective cohort studies and randomised controlled (intervention) trials. Being focused at the population-level, rather than focusing on individuals, the epidemiological approach allows the comparison of injured and uninjured groups of people for exposure to a number of potential injury risk factors [61]. Whilst epidemiological studies cannot fully prove that a risk factor causes injury, a rigorous study design will allow comparisons between the injured and uninjured groups for exposure to a risk factor to contribute to the decision about whether a causal relationship may be inferred [76].

In cross-sectional studies, information regarding injury status and injury risk factors is collected at a single point in time . Cross-sectional studies have the advantages of being quick and easy to conduct and are useful for determining the prevalence of injury cases and risk factors for a defined population [66]. The major disadvantage of cross-sectional studies is that data regarding exposure to risk factors and the presence or absence of injury are collected simultaneously. This means that these type of studies cannot provide evidence for a cause-effect relationship between the risk factors and injury [77], but may provide useful information for hypothesis generation [78].

Case-control studies assemble a group of athletes who are already injured and compare them with a group of athletes who are not injured (control group). The athletes are questioned about their past exposure to potential risk factors [63, 79]. The injured and uninjured athletes are then compared to determine if there are significant differences between the groups for exposure to any of the risk factors, however the actual risk of injury cannot be determined because the underlying population is not known [63]. Case-control studies have the advantages of being relatively quick to conduct, being relatively inexpensive and they are especially useful when the injury being studied is rare [50]. If the injury being studied is rare, a prospective cohort study would have to enrol many more people just to ensure that there were sufficient cases for statistical analysis, whereas a case-control study can easily identify the required number of cases. A disadvantage of this study design is that the question of reverse causality may arise [80]. Because exposure to risk factors is determined after injury has occurred, it may be possible that the injury caused the risk factor, rather than the risk factor causing injury. Therefore, it is essential in a case-control study that accurate information regarding exposure to the risk factor prior to injury is obtained so that a temporal association can be identified. Case control studies may be subject to inaccurate or biased recall of exposure to injury risk factors and injury history on the part of the participant [80]. However, accurate information regarding exposure to risk factors and details of injuries sustained may be obtained using detailed records kept by coaches or doctors.

Prospective cohort studies have been described as a natural experiment [70]. In prospective cohort studies, uninjured athletes are recruited and the exposure status of each participant is measured. The athletes are then followed longitudinally to record the occurrence of injury, and the injured and uninjured groups are compared for exposure [80, 81]. Some prospective cohort studies also collect data regarding potential injury risk factors in a baseline screening, such as flexibility, muscle strength and athletic technique. Comparisons can then be made between the injured and uninjured groups to determine if there were any differences in the risk factors at baseline.

Prospective cohort studies overcome the issue of recall bias that may be encountered in case-control studies, as the exposure to risk factors is clearly established before injuries occur [80]. Also, because injuries are reported as they occur, the researchers can check the details of injury events and make sure that the injuries are correctly classified [80]. For example, if the athlete is providing the information about an injury, further details can be obtained from a coach, parent, trainer or doctor. Another advantage of prospective cohort studies is that the estimates of risk obtained, according to the exposure to the risk factors, are true risks for the groups studied [80]. Because exposure and injury are recorded after the athletes have been recruited into the study, it is possible to identify a temporal association between the proposed risk factor and injury. For these reasons, the prospective cohort study design has been adopted in the program of research described in this thesis.

However, the limitations of prospective cohort studies are acknowledged. Prospective cohort studies can be expensive if the outcome of injury is rare, as a large number of athletes will need to be recruited into the study to enable meaningful statistical analyses [82]. Prospective studies can take a long time to complete, as there needs to be sufficient time for the required number of injuries to occur [81]. Also, only those potential risk factors defined and measured at the beginning of the study can be investigated [63].

Randomised controlled trials (RCTs) (also known as intervention studies) randomly assign athletes to one of two exposure groups: a treatment group and a control group [65]. It is not a realistic option to use the RCT design to identify injury risk factors (as it would involve deliberating exposing a group of people to potentially harmful exposures), however the RCT can be used to determine the effect of removing injury risk factors through the implementation of a preventive intervention [81]. For example, the research described in this thesis may identify associations between the factors measured and risk of injury. Based on the findings of this research, an RCT could then be conducted to determine the effect of introducing an intervention to reduce the effects of the identified risk factors.

In an RCT, the treatment group is exposed to a specified intervention, while the control group is not. Groups are then typically followed prospectively to determine any differences in injury occurrence that may be attributed to the intervention [81]. Because of the randomisation used in RCTs, the issues of bias and confounding encountered in other study designs are generally reduced [80]. However, as with prospective cohort studies, disadvantages of RCTs may be the length of time required to record the required number of injury cases and the ensuing cost of conducting such studies. Another disadvantage is that they can usually only investigate an intervention for a single risk factor, whereas the other study designs allow the investigation of multiple potential risk factors.

A2.7 The epidemiology – biomechanics interface in sports injury research

In 1996, Winston and colleagues promoted a new approach for injury control research, combining the principles of biomechanics and epidemiology [80]. They stated that injury epidemiologists, often working with clinicians, use statistical analyses of research data to identify specific injury-producing circumstances, as well as evaluating specific interventions [81]. However, epidemiological studies can lack detail regarding the biomechanics and kinematics describing the mechanism, or inciting event, of the injury [81]. A strength of biomechanics research is the ability to establish an understanding of the causal mechanisms for selected movements [80]. With an understanding of the mechanics of injury, prevention strategies can be further developed, such as changes to equipment, improvements in technique and development of strength and flexibility programs [70]. By adopting an interdisciplinary approach, research may lead more efficiently to real world solutions and successful injury prevention strategies [63, 70]. This requires combining the biomechanical concepts described in section A2.4, with the epidemiological approaches illustrated in section A2.6.

A2.8 An overview of cricket injury research

The research program described in this thesis focuses on investigating risk factors for injury to cricket fast bowlers. According to the model of injury prevention proposed by van Mechelen and colleagues [25] and the TRIPP framework developed by Finch [25] that were described in section A2.3, the first stage in the injury prevention process is to conduct injury surveillance, which is crucial for informing all other stages [25].

In a review of the relevant literature in 1999, Finch and colleagues reported that few studies had examined the incidence of cricket injuries during a season and investigated the risk factors contributing to the occurrence of injury [24]. At the time of this review, the only well-conducted epidemiological studies of cricket injury had been undertaken in South Africa [59, 83]. Other smaller studies had supplied some basic injury information about the injuries sustained by cricketers [25, 84]. Data from hospital emergency department surveillance systems had provided most of the Australian data on cricket injuries [64, 68]. The limitations of these data were described in section A1.2. Finally, Australian biomechanical studies in the 1980’s and 1990’s had contributed greatly to understanding the role of technique in injury to fast bowlers [31, 32, 48, 68, 85, 86], but apart from these studies, very little information was available regarding injury to cricket players.

Since the 1999 review [26], there have been a number of studies that have investigated the incidence and nature of cricket injuries, with a comprehensive profile of injury now provided for the elite levels of Australian [27, 37] and South African [38] cricket. Other studies have also contributed some limited information regarding the incidence of injury among elite English cricket players [39].

The next section of this Literature Review describes the studies that have documented the incidence and nature of cricket injuries at both the elite and amateur level. It is difficult to compare the injury rates between these studies due to the inconsistency in the definition of injury. Each study has adopted a different definition and has reported injury rates using differing measures of incidence, prevalence and severity. However, some consistent trends have been observed in these studies and as such, have provided very useful information to establish the priorities for continued cricket injury research.

A2.9 Incidence and nature of cricket injuries

Cricket Australia have implemented an injury surveillance system to monitor all injuries to elite cricketers in Australia. Injuries occurring to players in the six state squads (New South Wales, Queensland, Victoria, Tasmania, South Australia, Western Australia) and national squads have been surveyed prospectively since the 1998-99 season. The injuries occurring in the three preceding seasons (1995-96, 1996-97, 1997-98) were investigated retrospectively [40]. The matches monitored, called ‘major’ matches were first-class matches (Test matches, domestic four-day matches) and one-day international matches and domestic one-day matches, involving the Australian team or any of the state teams.

The primary recorder of injuries was the main team doctor or main team physiotherapist working with each team. The injury surveillance system recorded information about the date, diagnosis, mechanism and cause of the injury in addition to information regarding treatment received for the injury. Injury diagnosis was coded in a cricket-specific modification of the Orchard Sports Injury Classification System (OSICS) [41]. The mechanism of injury field included options such as a collision with another player; being hit by the ball; pushing off to run; gradual bowling; gradual running; slipping or tripping.

Prior to the 2004-05 season (when a new definition was adopted), an injury was defined as any condition that [42]:

- affected availability for selection of a team or squad member in a major match; and/or
- required surgery at any stage of the year; and/or
- during a major match:
    - caused a team member to be absent from the field for more than one hour; or
    - caused a bowler to finish bowling due to injury before the end of a normal over; or
    - prevented a bowler from being available to bowl for at least a session (in a first-class match) or as many overs as required by the captain (in a one-day match)
    - prevented a regular wicketkeeper from fielding in this position.

As outlined by the developers of this surveillance system, the reason for using the statement “affected availability for selection” rather than “missing a major match because of injury” is the nature of the various roles in cricket [48]. For example, a bowler may have been unable to bowl, but made himself available for selection (or played at a lower level) as a batsman only. Also, unless an injury met any of the above criteria, an injury that occurred during training or grade cricket was not included in the injury surveillance system. The authors have acknowledged that the definition of injury is limited, but that it was designed to ensure that all teams would apply the definition equally [29].

Injury incidence was calculated in two ways in this study [87]. Injury match incidence was reported using 12 players (per team) and the length of matches (in hours) in the denominator and was expressed as the number of injuries per 10,000 player hours. The calculation of exposure time is limited, as it estimates the length of matches, rather than recording the number of minutes each individual player was actually on the field. Injury seasonal incidence considered the number of injuries occurring per squad (25 players) per season (20 matches) and was adjusted for the squad size and length of season so that rates between different squads and seasons could be compared. A measure of injury prevalence has also been used and considered the average number of squad members not available for selection because of injury for each match, divided by the total number of squad members. It was expressed as a percentage, representing the percentage of players (on average) missing through injury at any given time for that team [50].

Using the data collected prospectively over five seasons (1998-99 to 2002-03 inclusive), the average injury match incidence was 21.0 injuries per 10,000 player hours and average injury seasonal incidence was 18.4 injuries per squad (20 players) per season (20 matches). The average injury prevalence for all players was 8.7%, but was much higher for fast bowlers (16.1%) as compared with spin bowlers (4.2%), batsmen (4.2%) and wicket keepers (1.2%) [35].

Recently, a consensus statement for injury surveillance in international cricket was established among the major Test playing nations (Australia, England, South Africa, New Zealand, West Indies and India) [88]. Due to the differing levels of medical support in these nations, the definitions previously used by Orchard and colleagues in Australian injury surveillance were modified for this international consensus statement, to ensure consistency amongst the various teams using the injury surveillance methods [29, 89]. In regards to the definition of an injury, the new international definition no longer considers injuries that occur whilst a player was fielding ("caused a team member to be absent from the field for more than one hour" [29]) or those only requiring surgery ("required surgery at any stage of the year" [29]) [29, 87]. The authors have suggested that this definition should be used to allow comparison of the results internationally, but that a broader, more inclusive definition of injury could be used for specific sub-studies [29].

Orchard and colleagues have adopted these new definitions in the Australian injury surveillance system and consequently re-analysed the data that had been collected previously [36]. Using the new international definitions, injury match incidence was 34.8 injuries per 10,000 player hours over the seasons 1997-98 to 2003-04, with the highest being recorded in one-day international matches (60.5 injuries per 10,000 player hours). The injury season incidence was 17.7 injuries per squad. The injury categories with the highest seasonal incidence were thigh and hamstring strains, groin and hip injuries, and lumbar injuries (other than stress fractures). Injury prevalence was 9.1% and increased over the six seasons, primarily because there were more matches to miss, with a greater number of matches being scheduled each season. Fast bowlers had the highest injury prevalence, with 16.2%, as compared with batsmen (4.7%), spin bowlers (4.6%) and wicketkeepers (1.7%). Lumbar stress fractures were associated with the highest injury prevalence [90]. On the basis of the Australian injury surveillance data, Orchard and colleagues have consistently recommended that identifying risk factors for injury to fast bowlers should be a priority for continued research [29, 87, 90].

Prior to the Australian injury surveillance system, the majority of published epidemiological data regarding cricket injuries were from South Africa. Stretch conducted several studies during the late 1980's and 1990's in South Africa examining the incidence and nature of injuries to cricketers [29, 87, 90]. A study that recruited adult provincial cricketers was conducted during the 1988-89 and 1989-90 seasons [90]. Responses to the questionnaires were obtained from 183 of the total sample of 308 male cricket players (59.4%), with a total of 88 injuries reported by the players. Stretch defined an injury as any physical damage that occurred during a match, practice or training session and prevented the players from completing the match, practice or training session. The principal finding of this study was that cricket injuries were common (48 injuries per 100 players per season). The incidence of injuries was higher in provincial players (71.6%) than club players (28.4%). Injuries occurred most often to bowlers (42.0%), particularly fast and fast-medium bowlers, as compared with fielders (40.9%) and batsman (17.1%). The majority of injuries occurred during matches, 47.8% of injuries prevented the player from returning to practice or play for 1 – 7 days and 23% were severe enough to prevent the player from returning to practice or play for more than 21 days. It was also reported that players were more likely to sustain injuries at the beginning or end of the season [87].

Another study by Stretch investigated the seasonal incidence and nature of injuries sustained by adolescent schoolboy cricketers in South Africa during the 1989-90 and 1990-91 seasons [87]. Responses to the questionnaires were obtained from 116 of the total sample of 196 male cricket players (59%), with the data being collected during the off-season. The definition of injury that was used with club and provincial players [29] was also used in this study. Stretch reported that the pattern of injuries to schoolboy cricketers was similar to that of club and provincial players, with an overall seasonal incidence of injury of 49 injuries per 100 players per season. A total of 57 injuries were reported, and as with club and provincial players, bowlers were most often affected (47%). Injuries occurred with equal frequency during matches and practice, particularly during the early and late parts of the season. In regards to injury severity, 63.2% of injuries prevented the player from returning to practice or play for 1 – 7 days and 14.0% of the injuries were severe enough to prevent the player's return to play for more than 21 days [87].

A limitation of these studies with club, provincial and schoolboy cricketers, as identified by Stretch [29, 31], is the 59% response rates to the questionnaires. Stretch stated that injured players are probably more likely to respond to the questionnaire than non-injured players which would lead to an exaggerated reported incidence of injury. Also, there may be limitations associated with the self-reported injury data, in that players may not accurately recall the details of injuries that happened previously. This recall bias was discussed previously in section A2.6.

Stretch also conducted a longitudinal study to determine the incidence and nature of injuries sustained by elite South African cricketers over the 1998-99, 1999-00 and 2000-01 seasons [32]. The doctors and physiotherapists working with the South African national team and the 11 provincial teams were required to complete a questionnaire for all cricketers that presented with an injury. An injury in this study was defined as any pain that prevented the player from completing that particular match, practice or training session and caused the player to seek medical attention. Over the three seasons being surveyed, 436 cricketers sustained 812 injuries, with an average of 1.9 injuries per player. Of these 812 injuries, 149 were attributed to overuse. Stretch found that younger players (up to 24 years of age) sustained more overuse (59.3%) and bowling (56.9%) injuries than older players. All 14 lumbar stress fractures reported over the three seasons were sustained by younger players, with 13 of those being attributed to bowling. As with his previous studies, Stretch reported that the majority of injuries were as a result of bowling (41.3%) and most were first time injuries (ie. a new injury that was not a recurrence of an injury that had occurred previously) (64.5%). The severity of injuries ranged with 36.4% of the injuries only preventing the player from completing the session in which the injury occurred and 26% preventing the player from returning to practice or play for 1 – 7 days. However, 26.1% of the injuries prevented the player from participating in match or training sessions for more than 21 days [35].

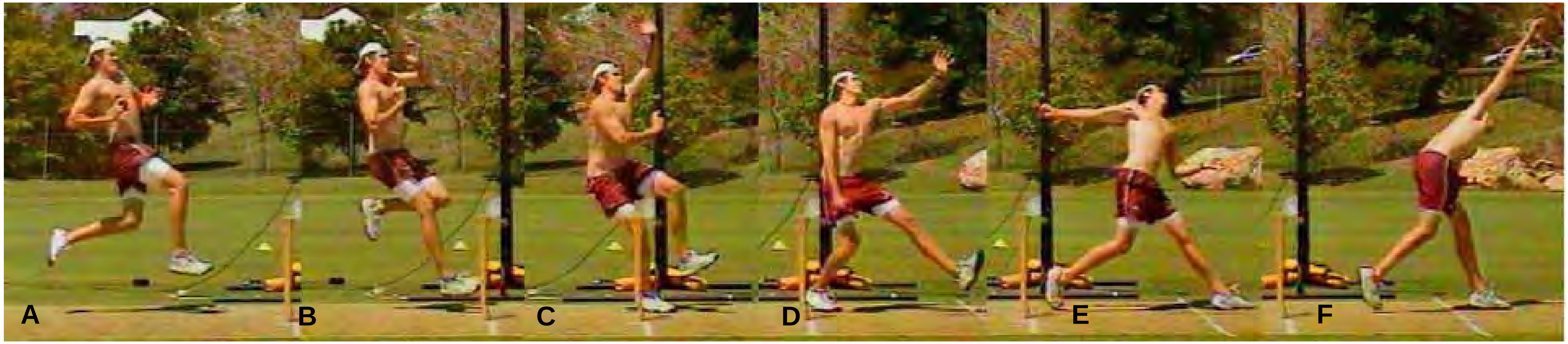
A retrospective study of cricket injury has been conducted in England [31]. The study examined acute injuries sustained by 54 adult professional cricketers at one English county club over the period 1985 to 1995 and reported a total of 990 injuries. In this study, injury was defined as the onset of pain or a disability, resulting from either training for or playing cricket, which caused the player to seek medical attention. The physiotherapist working for this county over the period of the study recorded injury information and found that there was a disproportionate number of injuries occurring at the start of the season. Overall, the injury rate was 57.4 injuries per 1,000 days of cricket. The incidence of injury was higher amongst bowlers (70.1 injuries per 1,000 days played) as compared with all-rounders (55.0 injuries/1,000 days), batsmen (49.4 injuries/1,000 days) and wicket keepers (47.3 injuries/1,000 days). Fast and medium-fast bowlers did not have a greater incidence of injury as compared with spin bowlers, however 30.8% of all fast and medium-fast bowlers sustained spondylolysis of the lumbar spine during the course of the study. Although the site and type of injury were outlined, the mechanism of injury was not reported in this study [31].

Because of differing definitions of injury, exposure time, incidence and prevalence in each of these studies, it is not possible to compare the injury rates. However, a consistent observation by each of these studies was that fast bowlers are the cricket players at the greatest risk of injury and they are most often affected by repetitive microtrauma injuries. This has established fast bowlers as the priority group for continued research to further understand the risk factors for injury.

A2.10 The action of fast bowling

Before discussing the risk factors for injury to fast bowlers that have been proposed in the literature, it is pertinent to provide a brief description of the action of fast bowling. An illustration of the fast bowling action is also provided in Figure 5. Fast bowling is a highly dynamic skill, with the fast bowler generating ball velocities up to 160km per hour [32]. It is a high impact activity, with the bowler experiencing a series of collisions with the ground in the run-up phase, followed by two large collisions during the delivery stride [31]. At back foot impact (Figure 5C), vertical ground reaction forces 2 - 3 times the weight of the body are generated [31, 32]. At front foot impact (Figure 5E), the forces are 5 - 9 times the weight of the body [32, 35, 88]. The forces in the musculoskeletal system (such as the bones, cartilages, tendons and muscles of the foot, ankle, knee, hip, pelvis, intervertebral discs and facet joints of the lumbar vertebrae) reflect the high ground reaction forces and the internal forces that are controlling the motion. At the same time, the trunk is flexing and extending laterally and rotating to achieve maximum delivery speed [88, 91].

Figure 5 The stages of fast bowling: pre-delivery stride through to ball release



As described in earlier sections of this Literature Review, injury can result from repetitive microtrauma of the musculoskeletal system, where a number of repetitive forces each lower than the critical limit of selected tissues produce a combined fatigue effect over time and reduce the tolerance of the affected structures to load [93]. This can be related to the action of fast bowling, where the load involved with bowling a single delivery may be lower than the critical threshold of the tissues, but the cumulative effect of bowling many deliveries during the course of a season may result in mechanical degradation of these tissues. Investigating the potential risk factors for these repetitive microtrauma injuries associated with fast bowling is the focus of this thesis.

A2.11 Potential risk factors for injury to fast bowlers

To date, low back injuries including spondylolysis, spondylolisthesis, pedicle sclerosis, intervertebral disc degeneration and muscular soft tissue injury have been the focus of the majority of injury risk factor research in fast bowling. These injuries first received attention after Dennis Lillee, a high profile Australian fast bowler, sustained a lumbar stress fracture in the early 1970's. Suggestions were made during the 1970's and 1980's that an increasing number of fast bowlers were suffering from back injuries and researchers subsequently began to investigate the potential risk factors for these injuries. Radiological studies have since confirmed the high rate of abnormalities to the bone and intervertebral disc for both adolescent and adult fast bowlers [40, 42, 93, 94], with the rate of these abnormalities exceeding that found in the general population or other athletic individuals [39, 95].

It has been proposed that injury and abnormal radiologic features among fast bowlers can be attributed to a combination of poor technique, poor physical preparation and overuse [50, 55, 57]. A number of specific risk factors for repetitive microtrauma injuries to fast bowlers have been proposed in the literature, and are discussed in detail in the following sections within the three main categories of bowling technique, physical characteristics and bowling workload.

A2.11.1 Bowling technique

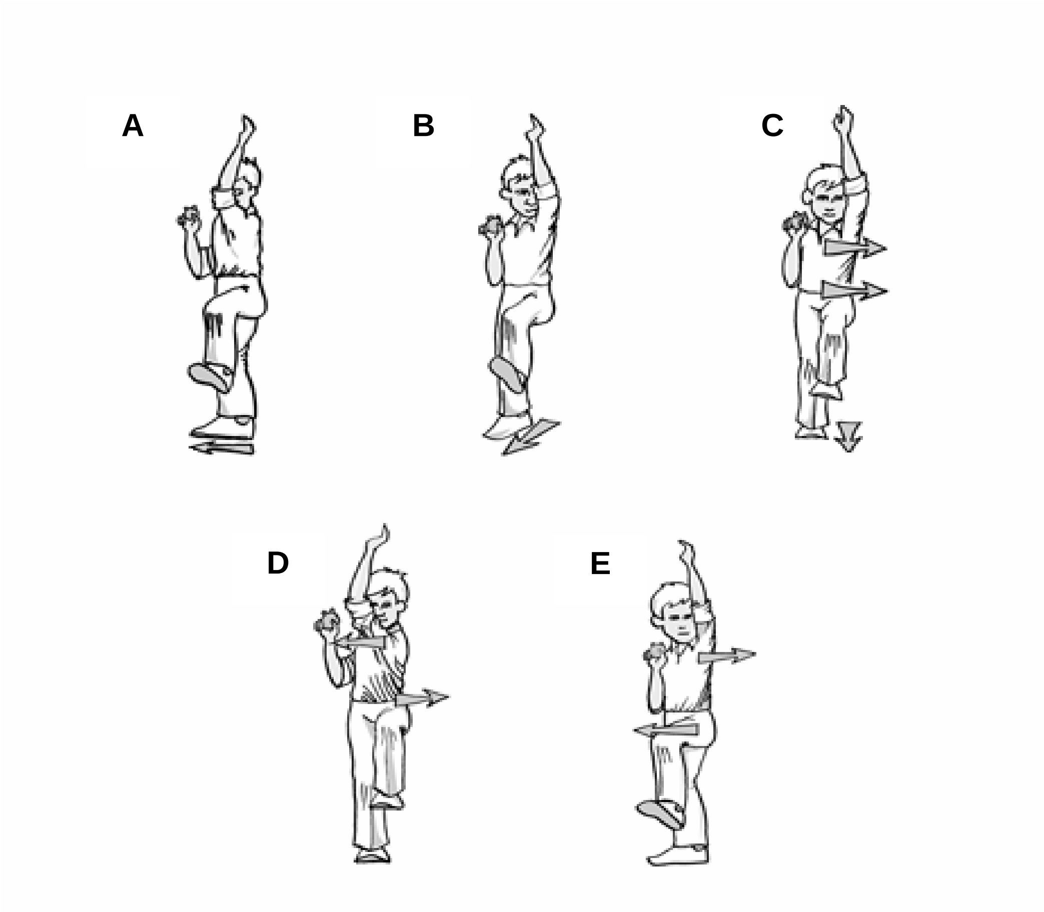
After initial concerns were raised regarding the large number of fast bowlers that were sustaining injuries, a series of biomechanical studies was conducted during the 1980's and 1990's that investigated the characteristics of different bowling techniques and their relationship with back injuries.

Early research identified and classified two main techniques in fast bowling: the 'side-on' and 'front-on' actions, as well as a combination of these, the 'mixed' action [40, 58, 96, 97]. More recent research has classified an additional bowling technique, the 'semi-open' action [98]. A number of different classification systems for bowling technique have been proposed, using criteria for the angles of shoulder alignment at back foot impact, rear foot alignment, hip-shoulder separation angles and/or counter-rotation angles of the bowler when preparing to deliver the ball to the batsman (these variables are described in further detail in the following sections) [38, 40, 42, 96, 98, 99]. Whilst guidelines for the classification of bowling technique have been developed, the techniques exist on a continuum and the boundaries between them are not fixed [40]. However, to provide an overview, illustrations showing the general alignment of the shoulders, hips and rear foot at back foot impact for the main bowling techniques are presented in Figure 6. A description of the basic characteristics of these main bowling techniques at back foot impact is also provided, summarising the more detailed descriptions provided in the literature [3, 4, 40, 42, 100-102].

In the side-on (Figure 6A), semi-open (Figure 6B), and front-on (Figure 6C) techniques, the bowler adopts body positions in which the hips and shoulders are in alignment with each other at back foot impact and there is no significant variation in this position until near the time of ball release [4, 38, 100]. In the side-on technique, the rear foot, hip and shoulder alignments are parallel to the popping crease at back foot impact. In the front-on technique, the rear foot points down the pitch towards the batsman and the hip and shoulder alignments are perpendicular to the popping crease. The semi-open technique is essentially midway between the side-on and front-on techniques, with the rear foot, hips and shoulders being diagonally aligned (45°) with the popping crease.

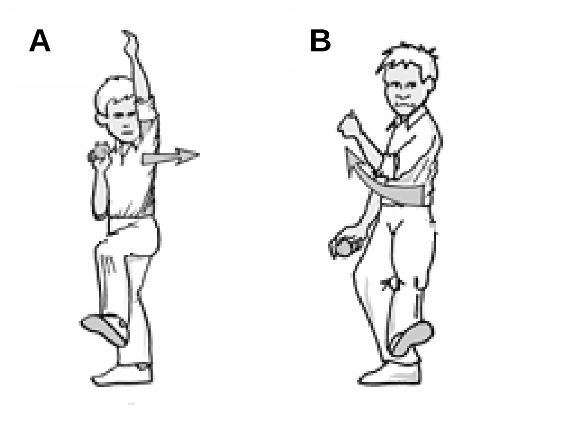
A mixed technique has also been identified, which is a mixture of the characteristics of the side-on and front-on techniques. The mixed technique can be identified at back foot impact, or in the phase between back foot impact and front foot impact [42]. At back foot impact, the mixed technique is characterised by bowlers adopting a position where the shoulders and hips are not aligned [40]. The shoulders may adopt a more side-on orientation than the hips and rear foot (Figure 6D) or the shoulders may be more front-on than the hips and rear foot (Figure 6E) [101].

Figure 6 Fast bowling techniques at back foot impact (A: side-on, B: semi-open, C: front-on, D and E: mixed) (drawings reproduced [4] with permission)



The mixed bowling technique can also be recognised in the phase between back foot impact and front foot impact, using measurements of shoulder counter-rotation (a term which is used in the international cricket literature and therefore adopted in this thesis). Counter-rotation is a measure of rotation of the shoulders in the transverse plane (using a line joining the acromion processes) about the longitudinal axis of the body [102]. As shown in Figure 7, counter-rotation occurs when the shoulders rotate from a more front-on position at back foot impact (diagram A), to a more side-on position just before front foot impact (diagram B), before rotating back again towards the batsman to a more front-on position for ball release [3].

Figure 7 Illustration of shoulder counter-rotation (drawings reproduced [38] with permission)



Shoulder counter-rotation is a measure of the composite of trunk and shoulder girdle movements projected onto the global transverse plane. It is determined by viewing the shoulders using footage captured from an overhead camera. The zero line runs directly down the pitch from the left shoulder (for a right-handed bowler), with the angle measured in an anti-clockwise direction [103]. First, the angle of the shoulders at back foot impact is determined. Then the alignment of the shoulders is calculated again at the point where the bowler attains the most side-on position (between back foot impact and front foot impact). Shoulder counter-rotation is calculated by subtracting the angle of the shoulders when they are most side-on, from the angle of the shoulders at back foot impact.

It is the mixed bowling technique, particularly the characteristic of excessive shoulder counter-rotation, that has consistently been associated with an increased risk of injury [3, 104]. The first study to show a statistically significant increased risk of back injury for bowlers using the mixed bowling technique was conducted by Foster and colleagues in the late 1980’s [105]. It also remains one of the few prospective cohort studies of fast bowling injury risk factors to be conducted. The study recruited 82 high performance adolescent fast bowlers (mean age 16.8 years), with a range of potential injury risk factors being investigated, including bowling technique. Bowlers underwent a series of tests prior to commencement of the 1986-87 season and during the season injuries were assessed by a sports physician, using computerised tomography (CT) scans to assist with making a diagnosis. During the course of the season, 38% of the bowlers sustained a back injury (11% sustaining a stress fracture to the lumbar spine and 27% sustaining a soft tissue back injury). In regards to the technique variables, bowlers who rotated their shoulders more than 40° from the shoulder alignment at back foot impact to a more side on position before front foot impact (counter-rotation) were more likely to sustain back injuries. Bowlers who sustained stress fractures tended to deliver the ball from a greater height (relative to their standing height) than the bowlers who were not injured during the season. The authors also acknowledged that the high rate of injury may also be attributed to the age of the bowlers, who could be more vulnerable to injury due to immaturity of the lumbar vertebrae [103].

After analysing the techniques of 15 elite fast bowlers at the Australian Institute of Sport (AIS), Mason and colleagues developed a model for fast bowling which they proposed would allow bowlers to maintain bowling delivery speed, yet reduce the risk of injury [3]. They collected information regarding the injury history of the bowlers, using details provided by the bowlers. Selected parameters of bowling technique were determined with biomechanical analysis. Technique characteristics which were common to bowlers who had experienced back, knee, shin or groin problems were identified. Bowlers who had previously suffered from shin soreness extended the raised front leg above horizontal when hip rotation was initiated and those with a history of groin injury tended to have a longer delivery stride. However, a limitation of this study is that the bowlers underwent biomechanical analysis and at that time reported their injury histories. Therefore, as was identified by the authors, there was no evidence to suggest that these technique characteristics caused injury as they may have been the consequence of injury [105].

In a cross-sectional study conducted in the 1989-90 season, the appearance of abnormal lumbar radiologic features (according to CT and MRI scans) was common in a group of 20 high performance fast bowlers (mean age 17.9 years) [3]. Eleven bowlers displayed bony abnormalities (spondylolysis, spondylolisthesis or pedicle sclerosis), 6 showed intervertebral disc degeneration or bulging and only 3 bowlers had no abnormal radiologic features. The bowlers also completed a range of testing after completing the CT and MRI scans, including a biomechanical analysis of technique. The appearance of abnormal radiologic features was attributed to a combination of factors, including use of the mixed bowling technique (front-on back foot placement and side-on shoulder alignment), excessive counter-rotation and an increased ball release height relative to standing height. As with the study by Mason et al [42], it was difficult to establish a cause-effect relationship due to the study design used. However, the findings did support those reported in the earlier prospective study conducted by Foster and colleagues [40].

More evidence supporting the association between the mixed bowling technique and an increase in degenerative changes of the spine was provided by Burnett and colleagues in a follow-up study of 19 young fast bowlers (mean age 13.6 years) [102]. The bowlers underwent MRI scans as well as an analysis of bowling technique. Bowlers were classified as using a side-on, front-on or mixed bowling technique. The bowlers were then tested again using an identical methodology 2.7 years later. The progression of disc degeneration in the thoracolumbar spine was found to be significantly related to the group of bowlers who used the mixed bowling technique in both sessions, as compared with bowlers who used the mixed technique in one session only [106]. Whilst the study was limited by a small sample size and the lack of bowling workload data, it still provided important information about the association between the mixed technique and the progression of disc degeneration.

A similar study was conducted with 41 junior fast bowlers (mean age 13 years), which investigated the relationship between bowling technique and lumbar disc degeneration after 3 years of educational intervention [3]. The bowlers attended six coaching sessions per year and video footage was provided to give feedback about each bowler's action. Lumbar disc degeneration was evaluated using MRI scans. The coaching intervention was shown to have no significant influence on the maximum front knee angle during the font foot impact phase, however a significant reduction in shoulder counter-rotation occurred over the four years of the study. The percentage of bowlers who were changed from using a mixed bowling technique to using safer side-on or front-on techniques increased from 19.5% to 66.7% after 3 years of the intervention. This study also reinforced the findings of the previous study by Burnett and colleagues [42], reporting that bowlers who used the side-on or front-on bowling techniques recorded significantly lower levels of disc degeneration, as compared with bowlers using a mixed bowling action [42]. This again highlighted the increased risk of injury or degeneration associated with the use of a mixed bowling action, including excessive counter-rotation.

Whilst measurements of shoulder alignment and shoulder counter-rotation had consistently been shown to be associated with degenerative changes and/or injury to the back, Stockhill and Bartlett proposed that it may not be appropriate to only consider the alignment of the shoulders, and that the alignment of the hips should also be assessed [94]. They suggested that shoulder alignment in itself may not be a predisposing factor for injury, as bowlers with the appropriate lower body orientation (hips rotating away from the batsman to the same degree as the shoulders) may not cause excessive rotation of the spine [94]. However, previous studies that had used two-dimensional biomechanical analyses were limited in their ability to provide this information.

To address this concern, research with elite Australian fast bowlers used a three-dimensional analysis of bowling technique to investigate the association between technique and back injury for the first time [40]. Portus and colleagues retrospectively analysed data that was collected between 1996 and 1999 for 42 fast bowlers. They employed different criteria to previous studies for the classification of bowling technique, using the shoulder alignment at back foot impact (a line joining each shoulder joint centre), shoulder counter-rotation and an additional measurement of the hip-shoulder separation angle at back foot impact. The hip-shoulder separation angle was calculated by subtracting the hip alignment angle (a line joining each hip joint centre) from the shoulder alignment angle. Portus and colleagues also measured the flexion and extension of the front knee between front foot impact and ball release to determine the role of the front knee in injury and bowling speed [94]. This study showed that the use of the mixed bowling technique was common, with 31 of 42 bowlers being classified as using a mixed bowling technique. Of the remaining bowlers, 2 were side-on, 6 were semi-open and 3 were classified as using a front-on bowling action. Of the 31 bowlers with a mixed technique, 9 were considered mixed due to a large hip-shoulder separation angle at back foot impact and excessive shoulder counter-rotation. Five bowlers had a large hip-shoulder separation angle at back foot impact but did not have excessive shoulder counter-rotation. The remaining 17 bowlers were classified as having a mixed technique solely due to excessive shoulder counter-rotation after having their hips and shoulders well aligned at back foot impact [42].

On examination of the association between technique variables and injury, shoulder counter-rotation was shown to be significantly higher in bowlers in the lumbar spine stress fracture group as compared with the group with no injury [102]. This supported previous research which had stated the importance of shoulder counter-rotation in the development of back injury [102, 106]. Being the first study to employ a three-dimensional analysis of technique, this study was able to provide additional information regarding the hip-shoulder separation angle that had not been measured in previous injury risk factor research. It was shown that the change in hip alignment contributing to hip-shoulder separation angle occurred well before the change in shoulder alignment during the delivery stride. Hence, Portus and colleagues concluded that since this hip rotation occurred so well in advance of shoulder rotation in the delivery stride, then the measure of hip alignment did not provide information that was necessary in the "real world" coaching environment [102]. They suggested that calculation of shoulder counter-rotation alone was sufficient to denote torsion of the trunk.

In the same study by Portus et al., analysis of technique also showed that bowlers who extended their front knee, or had a straight front knee, from front foot impact through to ball release experienced slightly higher ground impact forces (vertical and braking) [106]. Portus and colleagues suggested that this indicated that bowlers who flexed their front knee between front foot contact and ball release better absorbed the forces associated with front foot impact, thereby reducing the stress experienced by the body [99]. However, when examining this technique characteristic for its association with ball speed, it was found that bowlers who extended their knee bowled slightly faster than the remaining bowlers. Therefore, those bowlers with a straight, rigid front leg at ball release had bowled the ball at a slightly higher speed, but were possibly placing themselves at a greater risk of injury due to experiencing higher ground impact forces [99].

The findings of the study by Portus and colleagues [3] provided valuable information to inform the development of a technique analysis protocol for future research. However, it must be noted that a limitation of this study is that the injuries were included if they had been sustained prior to biomechanical testing, as well as after it. As described previously, this means that the technique variables may have been the result of some of these injuries, rather than the cause. The authors acknowledge that they assumed core movement patterns such as hip and shoulder rotations would not have changed significantly as a result of injury [3].

While several studies have identified a significant association between shoulder counter-rotation and injury and/or degenerative changes to the back, it is interesting to note that further analysis has also shown that counter-rotation has virtually no relationship with ball release speed [3, 40, 42]. This was supported by Portus and colleagues who reported that counter-rotation is possibly related to poorer accuracy during the second half of an 8-over spell [3]. Therefore, there is no performance benefit from adopting the mixed bowling technique that has been strongly linked to injury.

In summary, those studies analysing bowling technique have consistently identified an association between the mixed bowling technique, particularly the characteristic of excessive shoulder counter-rotation, and injury or degenerative changes of the lower back. However, Elliott has stated that shoulder counter-rotation is not a measure of lumbar torsional stress and that the precise effect of counter-rotation on lumbar spine mechanics has not been assessed [3]. Bartlett has provided support for this by acknowledging that the exact mechanisms of disc bulging and degeneration and neural arch fractures have not yet been established [3]. It has been proposed that the strong association between the mixed bowling technique and injury / degenerative changes may be due to greater mechanical loading [3] and rotational stress in the lumbar spine that are possibly encountered by bowlers using a mixed technique [3]. This loading, in addition to hyperextension of the lumbar spine and large peak vertical ground reaction forces may increase the risk of injury [3].

A2.11.2 Physical characteristics and preparation

Whilst biomechanical studies have provided an understanding of the role of certain parameters of bowling technique in injury, the role of the physical characteristics of fast bowlers in injury is not as well understood. Few studies have been conducted in this area, and those that have are limited by a small sample size. Nevertheless, these studies have contributed some information about the possible association between the physical characteristics and preparation of fast bowlers, with the occurrence of repetitive microtrauma injury.

Mackay and Keech proposed that in fast bowling, a full range of lumbar joint movement in flexion, extension, lateral flexion and rotation is required and that stiff joints at particular intervertebral levels may place extra force on existing hypermobile joints at other levels, resulting in injury [3]. They also postulated that tightness in muscle groups can cause forward rotation of the pelvis and increase lumbar lordosis [106].

In addition to collecting baseline information about the techniques used by fast bowlers, Foster and colleagues measured a range of kinanthropometric and physiological variables in their prospective study of 82 fast bowlers [99]. They reported that bowlers with a low longitudinal arch of the foot were more likely to develop a stress fracture, as were those with higher levels of shoulder depression strength and shoulder flexion strength for the preferred limb. The authors postulated that bowlers with a low arch may not be able to absorb the high impact forces during the landing phases of the delivery stride and that those with greater upper body strength may have exerted higher twisting forces on the spine whilst trying to achieve optimal ball velocity [107].

Elliott and colleagues also collected information regarding the physical capacities and the posture of 20 adolescent bowlers [100]. The only measure that was significantly associated with an abnormality of the intervertebral disc was poor hamstring or lower back flexibility. However, as was acknowledged by the authors, this could be a result of the intervertebral disc bulging, rather than the cause. This is because the bowlers completed the testing after their radiological status had been evaluated [103].

Another perspective was provided by Engstrom and colleagues, who reported significant asymmetries in the quadratus lumborum and psoas muscles in a group of adult elite fast bowlers [49].The mean age of these adult bowlers was not reported. The asymmetry between the dominant and contralateral sides of the body was significantly greater in the fast bowlers as compared with a control group, as determined by MRI scans [102]. Further research reported that similar patterns of disc generation and bone sclerosis were also seen in a group of junior fast bowlers (mean age not reported) [49]. Based on the findings of these studies, Engstrom and colleagues speculated that asymmetry in the quadratus lumborum muscle volume underlies asymmetric loading in the pars interarticularis and is therefore involved in the aetiology of lumbar bone stress injury [49]. However, no prospective research has been conducted to support this suggestion.

A2.11.3 Bowling workload

As with physical characteristics, limited research has investigated the role of bowling workload in repetitive microtrauma injuries to fast bowlers. Whilst many authors have recommended a sensible approach to bowling workload [40, 42, 45], little research has been done to provide evidence-based guidelines for the number of overs to be bowled in matches and training to reduce the risk of injury [40] even though it has been identified as one of the most important potentially reversible risk factors [43].

The majority of research that has investigated bowling workload has been limited by comparing the injured and uninjured bowlers according to the total number of sessions/deliveries bowled during an entire season, which may include bowling completed after injury. Due to the importance of distinguishing between injury risk factors and injury sequelae [43], it is important to only examine bowling completed prior to injury (if any).

The study conducted by Foster and colleagues in the late 1980’s was the first to prospectively monitor bowling workload [97]. The authors reported that there was a significant relationship between bowling workload and the occurrence of back injury being reported. Of the 32 bowlers who had bowled greater than the mean number of matches (mean = 17) for the group, 19 bowlers (58%) sustained a stress fracture or back injury. This was in comparison to the 38% injury rate for the whole group. Forty-one bowlers reported bowling in excess of 10 overs in a spell during the season (mean for group = 8.5 overs) and of this group, 27 reported abnormal lower back pain the following day [44]. However, the authors did not specify whether this abnormal back pain resulted in any lost match or training time. Whilst Foster and colleagues suggested that bowling too many overs in any single spell and/or bowling too many spells may lead to back injuries, it is unclear as to whether they examined workload prior to the occurrence of injury only, or workload for the entire season.

In their injury surveillance report, Orchard and James conducted further analyses to identify the possible relationship between match bowling workload and injury to first-class fast bowlers [4]. Univariate analysis of risk factors for bowling injuries found that bowling in the second match of back-to-back matches (defined as < 3 day break between first-class matches or < one day break between one-day matches) was associated with a significant increase in bowling injury risk. Bowling after enforcing the follow-on in a Test match was also associated with a significant increase in risk of injury [95]. Orchard and James have suggested that high match bowling workload seems to be particularly related to hamstring strains, side strains and shoulder injuries [108].

In a longitudinal study of cricket injuries in South Africa, 13 of the 14 lumbar stress fractures that were sustained by junior fast bowlers were attributed to overuse [109]. However, the actual workloads were not established. Stretch suggested that the reason for excessive bowling was due to the need for early specialisation and more bowlers playing for their school team as well as for a club team [45]. Another suggestion was that these junior bowlers had a much greater workload as they were bowling in practice sessions for the first-class teams to give the batsmen extended batting practice, whilst the first-class bowlers were allowed to rest [110].

Gregory and colleagues conducted a prospective cohort study with 70 English adolescent fast bowlers (mean age 15.3 years) during three months of pre-season indoor training and the first three months of the 1998 cricket season [29]. To determine match bowling workload, the participants in this study recorded how many overs and extras they bowled in matches in a bowling logbook. For training workload, the bowlers estimated the amount of time they spent bowling in the nets during training sessions and recorded how many other bowlers were sharing the same net so that the authors of the study could estimate how many balls were bowled at training. Injuries included in their study were those caused by bowling that impaired bowling performance or prevented the player from bowling and included acute and overuse injuries. A range of injuries were recorded in this study, including ankle sprains, patellofemoral pain syndrome and patellar tendinitis. Only three bowlers reported back pain that impaired or prevented them from bowling, with one of these bowlers sustaining a pars interarticularis stress fracture. The bowlers were categorised into four groups according to the total number of balls bowled during the 6-month period and the injury rate per 1,000 balls bowled was calculated for each of these groups. There was no difference between the groups and the authors concluded that there was no increased injury risk for those that bowled the most [66]. However, the fact there was no difference between the workloads of injured and uninjured bowlers may simply be because total workload for the entire 6-month study period was compared. Perhaps the injured bowlers could not bowl for a significant period of time after injury, thereby reducing their total seasonal workload.

In comparison to the English study, a prospective cohort study of 12 Australian first-class fast bowlers reported a significant association between high bowling workload and injury [42]. This study quantified the actual number of balls bowled in both matches and training sessions and investigated the association between workload and the occurrence of overuse injuries. For the seven bowlers who were injured, only workload prior to injury was reported. For the five uninjured bowlers, workload for the entire season was reported. This study showed that high weekly workload placed a bowler at a much higher risk of injury, as bowlers who bowled in 5 or more sessions in a week may have been at greater than 4 times the risk of injury. Injured bowlers also bowled an average of 70 deliveries more per week than uninjured bowlers, with those bowling above 203 deliveries per week being 6 times more likely to sustain an injury. The period of rest between sessions also played a role in the occurrence of injury. On average, injured bowlers had rested only two days between each bowling session, whereas uninjured bowlers had rested for three days. These findings suggest that rest periods may be as important in preventing injury as reducing the number of deliveries bowled. This study was limited by a small sample size, however a consistent association between high workload and injury was observed [42].

A2.12 A brief summary of risk factors for injury to fast bowlers

Biomechanical research of bowling technique has consistently identified an association between the mixed bowling technique (particularly the characteristic of excessive shoulder counter-rotation) and injury or degenerative changes to the lower back [35, 36, 87].

The front knee angle during the delivery stride has also been identified as a potential risk factor for injury, due to the possible role of the knee in the attenuation of impact forces [35, 47]. Flexing the front knee may help attenuate the impact energy and therefore decrease the ground reaction forces. It has been suggested that the front knee should be slightly flexed to assist in the absorption of these forces [47].

A high ball release height, when expressed as a percentage of standing height, also appears to be related to injury [46]. This may be due to the bowler decreasing joint angles at front foot impact to help reduce the influence of ground reaction forces, which results in a reduction of the ball release height [106]. It is also likely to be related to the length of the delivery stride and the extent of trunk flexion and lateral flexion [42].

The relationship between physical characteristics and injury is not as well understood. Foster and colleagues have identified a significant association between a low longitudinal arch of the foot, as well as high levels of shoulder depression strength and shoulder flexion strength in the bowling arm [40]. Elliott and colleagues reported an association between poor hamstring or lower back flexibility and an intervertebral disc abnormality, however the cause-effect relationship was unclear [3]. Whilst an asymmetry in the paraspinal muscles for the dominant and contralateral sides of the body has been identified in fast bowlers, it is not known whether this contributes to an increased risk of back injury [3, 4, 102]. In regards to the relationship between bowling workload and injury, several studies have reported an increased risk of injury for bowlers with high bowling workloads [38, 40].

A2.13 The effects of repetitive microtrauma on the various human tissues

As described in section 2.10, fast bowling is a high impact activity which produces vertical ground reaction forces 2 - 3 times the weight of the body at back foot impact [3, 42] and 5 - 9 times the weight of the body at front foot impact [4, 40, 42, 43]. These forces are then transmitted through the bones, cartilages, tendons and muscles of the foot, ankle, knee, hip and pelvis to the intervertebral discs and facet joints of the lumbar vertebrae [44, 97]. The studies presented in section 2.9 demonstrated that fast bowlers are the cricket players at the greatest risk of injury and that they suffer from a range of injuries. Bony and soft tissue back injuries have been the focus of the majority of injury risk factor research to date as they can potentially limit participation in the game for extended periods, more so than any other type of injury [42, 46, 50].

Whilst the load involved with bowling a single delivery may not exceed the critical limit of the tissues of the body, the cumulative effect of the repetitive stress encountered in fast bowling during the course of a season may result in mechanical degradation of these tissues. This section of this Literature Review discusses the potential effects of this cumulative loading on the various tissues of the musculoskeletal system.

Biomechanical research has provided an understanding of the effects of maximal, instantaneous loads on human tissue and the different tissues' tolerance to these impact injuries [40, 93]. This information has subsequently been used in the development of injury prevention guidelines, such as occupational lifting tasks [40]. However, the effects of cumulative loading are not as well understood [42].

As described previously, injuries can also result from an accumulation of damage from repeated microtrauma. Tissue has the ability to undergo adaptation to stress and to recover from this repeated microtrauma. However, repeated exposure over a prolonged period may impede complete recovery, causing residual strain [94]. This residual strain is most likely to occur when the adaptive changes are insufficient to compensate for the adverse biomechanical effects of exposure to stress [93]. An accumulation of residual strain may facilitate injury, due to a progressive reduction in stress tolerance capacity from the gradually increasing residual strain [92, 95]. Essentially, this means that the threshold at which the tissues fail is reduced because of this cumulative fatigue. The number of loading cycles required prior to failure may range from a few, to many millions [40].

All biological tissues are viscoelastic, therefore their mechanical properties are time and strain-rate dependent [111]. Materials change their shape when subjected to external loads, which is described as ‘deformation’ [42]. Viscoelastic tissues lose energy to heat during deformation and the return following unloading is retarded, resulting in a return path different from the initial path during loading [112]. Essentially, this means that energy is lost during the loading-unloading cycle [113]. The differing viscoelastic properties of the various tissues of the human musculoskeletal system determines how quickly recovery can occur [55, 112, 114]. Each tissue possesses unique characteristics and has different responses to loading. These characteristics are described below. The following summary is not intended to provide comprehensive clinical details of the effects of repetitive microtrauma on bone, cartilage, tendons, ligaments and muscle, but to present a brief summary. Further clinical details can be obtained from the papers referred to in the text.

Bone

Although bone can withstand substantial stresses when loaded only once, as the number of cyclic loads increases, the ability of a bone to withstand the stress decreases exponentially [55]. With decreasing load levels during continuous and cyclic loading, there is an increasing amount of deformation in the plastic region of bone [55]. In healthy bone, if the damage is not excessive, remodelling occurs around the microscopic cracks caused by the fatigue, and new bone is deposited [60]. However, if the damage is excessive and the normal remodelling process cannot keep up with the repair, these dispersed microscopic cracks may weaken the bone [55, 60]. The accumulation of this fatigue microdamage may then produce a stress fracture, due to the repetitive, cyclic loads placed on the weight-bearing bones [60]. Stress fractures may occur in virtually any bone in the body, but most commonly affect the tibia, metatarsals, fibula, tarsal navicular, femur and pelvis [60].

Brukner has suggested that there is a continuum of bony changes identifiable in radioisotopic imaging [60]. The earliest change in the continuum, called bone strain, is identified by an uptake of radioisotope at non-painful sites, representing bony remodelling at an early level [55]. The next level, called a stress reaction, is recognised by a painful, tender focal area of bone which demonstrates an increased uptake of radioisotope, but not yet sufficient to be classified as a stress fracture [115], and a fracture is not visible on CT scan. Finally, the stress fracture is identified by mild, moderate or severe localised pain, with increased uptake of radioisotope [60] and a fracture is visible on CT scan.

Cartilage

As with many load-bearing connective tissues, there is an amount of use that provides optimal function for cartilage [60]. If the cartilage is used too little or too much, a breakdown in the quality of cartilage can occur [60]. In a study of full thickness chondral lesions in a group of athletes, Gobbi and colleagues reported that only 21% of these injuries were related to a specific traumatic incident [60]. It must be noted, however, that the aetiology of injury in this study was self-reported.

Tendons and ligaments

Both ligaments and tendons are made of collagen, which means that they are both subject to unrecovered deformation, as described previously. There are differences between tendons and ligaments in the density and arrangement of the collagen fibres [60]. Tendons are responsible for force transfer from skeletal muscle to bone to generate joint movement [60, 116, 117], while ligaments provide joint support and stability [117]. This means that tendons differ from ligaments in that they not only connect to bone but also to muscle [117]. In regards to transference of force, the musculotendinous junction is equally as important as the tendon-bone junction, since high local stress can occur and cause injury [117]. Rarely is a single load so high that it exceeds the tensile strength of the collagenous structure and causes failure of the tissues [117]. More commonly, injury is the result of repetitive exertions [60].

The connective structure of tendon creates three structural zones: the body of the tendon itself; the connections of tendon with bone; and the connections with its accompanying muscle [60]. Injuries to the tendon may be indirect, resulting from excessive tensile loads applied to the tendon structure [118]. Tendinopathies are traditionally considered repetitive microtrauma injuries, involving excessive tensile loading and subsequent breakdown of the tendon [55].

Muscle

Skeletal muscle is comprised of two basic elements: active contractile components and fibrous connective tissues (including sarcoplasm, sarcolemma, endomysium and collagen fibres that filter through the muscle belly) [55]. The active contractile components are rarely affected by unrecovered deformation [60]. However, the fibrous connective tissues within the muscle may be prone to injury due to unrecovered deformation, as was described previously for tendons and ligaments. It has been argued that repeated demands on a muscle may cause it to shorten due to the cycle of microtrauma, scar formation, and more microtrauma with continued use [119].

With the recent advent of MRI scans for the assessment of soft tissue injuries, it is possible to identify the site of injury to the muscular unit. Clinical studies that have investigated the actual site of muscle strain injury using MRI have shown that the majority of these injuries (ranging from 93% to 100% of all injuries) occurred at the musculotendinous junction, rather than the belly of the muscle [55, 120]. The musculotendinous junction is comprised of both tendinous fibres and muscle tissue [55]. Therefore, the findings of MRI studies support the notion that these injuries may be associated with repetitive microtrauma and unrecovered deformation. However, it is acknowledged that the aetiology of muscle strain injuries, as with all other musculoskeletal injuries, can be attributed to a complex interaction of multiple risk factors.

A2.14 The vulnerability of the adolescent musculoskeletal system to injury

The properties of these musculoskeletal tissues differ between adults and adolescents. It is therefore essential that injury prevention strategies, programs and recommendations that are designed for adults are not simply extrapolated to adolescents. This is because the young athlete is not simply a small adult [55] and their musculoskeletal system may be particularly vulnerable to injury due to the unique physical and physiological processes of growth [60]. Anatomical and biomechanical differences between children and adults account for the differing patterns of injury seen in different age groups [60]. The risk factors for injury that are exclusive to the young athlete include the adolescent growth spurt and susceptibility to growth plate injury [119]. As part of the growth process, the elongation of the musculotendinous units occurs as a secondary response to the lengthening of long bones at their growth plates [60]. It has been proposed that joint tightness can develop during phases of rapid bone growth, such as the adolescent growth spurt, when the bones lengthen faster than the musculotendinous units [55, 121]. This can result in reduced flexibility and dynamic muscle imbalances [122, 123].

The developing musculoskeletal system is particularly vulnerable to overuse, with sites of vigorous development in long bones and musculotendinous attachments being potential injury areas [124, 125]. The most serious overuse injuries for young fast bowlers are those to the pars interarticularis, as they can potentially limit participation in the game for extended periods [126-128].

The spine of an adolescent differs from that of an adult in numerous respects [127]. Throughout its maturation, the vertebral column undergoes enormous cellular, biochemical and structural changes that greatly influence its response to external forces [73]. Adolescent athletes are much more likely to have injury to their posterior vertebral elements (which includes the pars interarticularis) as the underlying cause to their back pain when compared with adults [73]. Differences in the structure of the intervertebral discs, ligaments, muscles and vertebrae of the spine help to account for the differing patterns of injury seen. In a number of activities, but particularly those which require repetitive hyperextension of the lumbar spine (such as fast bowling), low back pain may exist as rapid growth of the vertebral bodies is not matched by the dorsal soft tissues [61].

In children and adolescents, the intervertebral disc is more elastic and more hydrophilic and is more resistant to injury than the vertebra [73]. The collagen content of the disc is lower in adolescents and the concentration of elastic fibres in the disc is higher [61]. This decrease in collagen and increase in elastic fibres renders the disc less stiff and less resistant to deformation. The increased elasticity of the intervertebral disc may therefore allow a greater proportion of torsional forces to reach the facet joints and hence stress the pars interarticularis [40, 61, 129]. The decrease in stiffness of the intervertebral disc is also a principal cause for the increase in mobility which is seen in the immature spine [111].

The ligaments and surrounding soft tissue structures of the immature lumbar spine are also more elastic [42] and this also contributes to increased mobility in the adolescent spine. The compressive and tensile mechanics of these spinal soft tissues are decreased in the immature spine, hence causing more stress to be borne by the vertebrae [130]. The muscles which surround the spine are not as well developed in adolescents as they are in adults [131]. It is possible that spinal stability is more likely to be compromised in the presence of less developed musculature, since a major part of the stability of the spine is maintained by active forces generated from contraction of paraspinal muscles [126].

There are also differences in the structure of the iliolumbar ligament between children and adults. The iliolumbar ligament has been shown to maintain torsional stability at the lumbosacral junction [129] and to be a stabiliser of the sacroiliac joint [130]. An immature lumbar spine may have compromised stability at the lumbosacral junction and sacroiliac joint because of incomplete formation of the iliolumbar ligament until the third decade of life [132, 133].

Additionally, there are major differences between adolescents and adults with respect to the spinal vertebrae. The developing spine has abundant ossifying growth cartilage [132] and this is vulnerable to deforming compressive and tensile forces [132]. Complete ossification of the posterior vertebral elements does not occur until about 25 years of age [128, 132] and in the immature spine intervening cartilage is present. This intervening cartilage is gradually replaced by bone [131]. In the fifth lumbar vertebra there can be two areas of ossification in each half of the vertebral arch which are united by cartilage between the superior and inferior articular processes. Consequently there could be an increased risk of separation and possible injury in this area whilst ossification is occurring [128]. This part of the vertebra, which intervenes between the superior and inferior articular processes, is the pars interarticularis [134] and it is well recognized that this is the most common lumbar injury in adolescent athletes [135]. As vertebral bone ossifies from its original cartilaginous template into its adult form, the basic mechanical functions of the spine also mature.

A2.15 Summary of literature review and the rationale for developing a program of research to investigate risk factors for repetitive microtrauma injuries to cricket fast bowlers

This section summarises the concepts that have been described in the Literature Review and provides the rationale for the development of the research program described in this thesis.

A2.15.1 Current knowledge regarding injury to cricket fast bowlers

Fast bowlers have been identified in the cricket literature as the players at the greatest risk of injury [128, 135-139]. Biomechanical studies have provided comprehensive information regarding the role of bowling technique in injury [29, 50, 126, 132, 139, 140]; some studies have investigated the association between bowling workload and injury [31, 32, 35, 87], and others have examined the role of physical characteristics and preparation in injury [40, 42, 88].

As described in the Introduction (Chapter A1), a limitation of much of the cricket research conducted to date has been the use of cross-sectional and retrospective study designs, which means that it is difficult to establish cause-effect relationships between the risk factors investigated and injury. Whilst previous studies have helped identify the technique, physical characteristics and workload factors associated with injury to fast bowlers, it is essential that continued prospective research builds on this information and develops a further understanding of the injury risk factors relating to repetitive microtrauma injuries for both adolescent and adult fast bowlers.

Another limitation of risk factor studies reported in the literature is that many have used specialised equipment and laboratory facilities to test fast bowlers, and the degree to which the testing procedures can be adopted in the cricket "real world" is unclear. It is important that reliable field-based screening protocols are developed so that cricket coaches and medical staff are able to easily and inexpensively monitor fast bowlers on an ongoing basis.

A2.15.2 The study designs, conceptual frameworks and models used to develop the program of research described in this thesis

The information that has been provided in the relevant cricket literature, as well as the limitations and gaps of studies already conducted, were used to establish the priority areas for continued research. In conjunction with the frameworks, models and concepts discussed in this Literature Review, a research program to investigate potential risk factors for repetitive microtrauma injury to fast bowlers was designed.

The TRIPP framework developed by Finch [102] has described sports injury prevention as consisting of a number of sequential stages. Previous studies have addressed the first stage of this process by describing the incidence and nature of cricket injury. It has been identified from these studies that fast bowlers are the players with the highest rates of injury. The second stage in the process of sports injury prevention is to establish the aetiology and mechanisms of injury. Whilst several studies have been conducted in this area (as described in section A2.11), some are limited by small sample sizes or the use of cross-sectional and retrospective study designs. Addressing the second stage in the process of sports injury prevention is therefore the focus of the research described in this thesis.

In section A2.6, the advantages and disadvantages of different epidemiological research designs were listed. The prospective cohort study is a preferred design as it allows injury and exposure data to be collected prospectively and therefore avoids recall bias. As suggested by de Loes, the number of participants and the time spent at training and competition, for both injured and uninjured participants, are essential epidemiological variables and allow the expression of incidence rates according to the amount of exposure [106]. The prospective cohort study design was therefore chosen for investigating the potential risk factors for injury to fast bowlers.

Whilst the research is primarily epidemiological, the benefits of incorporating biomechanical perspectives have been identified, as summarised in section A2.7 [3, 42, 46, 87, 94, 141]. Therefore, the research described in this thesis has used an interdisciplinary approach to address the research questions that were listed in section A1.3.

Several models of sports injury aetiology have been discussed in the scientific literature [40, 42, 47] and were presented in section A2.4. For the purposes of this research program, the model proposed by Bahr and Krosshaug was adopted. This conceptual model was used to describe the relationship between load (as a mechanism of injury) and load tolerance (influenced by intrinsic risk factors) with the outcome of repetitive microtrauma injury to fast bowlers. As described recently by McIntosh, injury interventions should focus on modifying the loads applied externally and internally to the body; by either reducing the load below relevant injury tolerance criteria, or improving the body’s capacity to tolerate certain patterns of loading [44]. In some situations it may be possible to develop interventions that increase the body’s tolerance through training. Alternatively, interventions could be developed that prevent tolerance levels for specific structures decreasing during prolonged exposure, such as time management, training plans and player rotation [68].

A2.15.3 Designing a sequential program of research to investigate potential risk factors for injury to fast bowlers

It has been proposed that injury and abnormal radiologic features among fast bowlers can be attributed to a combination of poor technique, poor physical preparation and overuse [21, 22, 142]. Whilst biomechanical studies have provided important information about the association between certain technique characteristics and injury, there is limited evidence to support the role of workload and physical characteristics in injury.

In meetings of cricket coaching staff and forums of cricket sports science and medicine staff in the late 1990's, bowling workload was identified as a priority area for further aetiological research. Bowling workload guidelines had been proposed for fast bowlers as part of Cricket Australia's National Pace Bowling Program (NPBP) which recommended the maximum number of deliveries to be bowled in matches and training sessions for players aged <19 years [20]. Preliminary investigations had identified an association between high workload and injury [23, 24], however little information was available to provide evidence for these guidelines. In considering occupational health and safety principles, cricket associations requested information to guide the training and match programs for their contracted fast bowlers.

Therefore, a study investigating the relationship between bowling workload and injury was established as the initial stage of the program of research described in this thesis. It is acknowledged that a range of intrinsic and extrinsic risk factors contribute to injury, and that this first study was limited by only investigating the association between workload and injury. However, bowling workload had been identified as a priority area for further research by cricket administrators, sports medicine staff and within the relevant scientific literature. Limited resources and research funding also prevented the conduct of a larger scale project investigating a range of potential risk factors. Therefore, the study only investigated the association between load (as measured by bowling volume) and injury. This workload and injury study recruited adult first-class fast bowlers and was conducted over the 2000-01, 2001-02 and 2002-03 cricket seasons. Cricket Australia provided research funding for this project.

Preliminary analyses of the data collected in the first season of the study conducted with adult fast bowlers raised concerns about the appropriateness of the fast bowling workload guidelines for adolescent bowlers [25], which were based on best practice rather than scientific evidence. Therefore, a study investigating the relationship between bowling workload and injury for adolescent fast bowlers was established as the second stage of the program of research described in this thesis. As with the first study, this study only investigated the association between load (as measured by bowling volume) and injury. This study recruited adolescent fast bowlers and was conducted over the 2002-03 cricket season. Cricket Australia and the NSW Sporting Injuries Committee provided research funding for this study.

The third and final study in the program of research described in this thesis was developed using information that had been provided by the first two workload studies, as well as research studies described in the cricket scientific literature. These two workload studies had demonstrated that bowling workload was significantly associated with an increased risk of injury to fast bowlers, but it was acknowledged by administrators and funding boards that to develop a solid evidence base for broader fast bowling injury prevention strategies that it was also necessary to investigate a range of potential risk factors. The third study considered bowling workload, technique measures and physical characteristics and investigated the association between load (as measured by bowling volume) and load tolerance (intrinsic risk factors such as bowling technique, fitness and body composition) with the outcome of injury among fast bowlers. This study recruited 91 adolescent and adult fast bowlers. Cricket Australia provided research funding for this project.

Another aim of this study was to determine the reliability of field-based screening protocols that were used in the baseline screening of the 91 bowlers participating in the prospective cohort study. These screening protocols included a musculoskeletal assessment, analysis of bowling technique and fitness assessment. A statistical method for concurrently determining the inter- and intra-observer reliability of the protocols was selected and used to establish the reliability of these field-based screening protocols. Ideally, a reliability assessment of the screening protocols would have been conducted to determine the inter- and intra-observer reliability of the tests prior to commencement of the prospective cohort study. Unfortunately, due to the timing of the notification of the successful funding application, it was not possible to conduct a reliability assessment before the study started. Therefore, a reliability assessment was conducted after the baseline screenings for the prospective cohort study had been completed.

As described in section A1.3 of the Introduction, the primary aim of this thesis is to describe the epidemiology of repetitive microtrauma injuries and to identify the risk factors for these injuries to fast bowlers. The specific research questions were listed in section A1.3 on page 20. Part B of this thesis describes a series of three sequential studies conducted with adolescent an adult fast bowlers. Part C describes a method for the concurrent assessment of inter- and intra-observer reliability and the results of this assessment.

PART B THE EPIDEMIOLOGY OF INJURY AND RISK FACTORS FOR INJURY TO FAST BOWLERS

B1: Bowling workload and the risk of repetitive microtrauma injury to adult fast bowlers

This chapter describes the results obtained from the workload and injury study conducted with first-class fast bowlers during the seasons 2000-01, 2001-02 and 2002-03. An analysis of data collected in the first two seasons (2000-01 and 2001-02) has already been published in a peer-review journal. A copy of this paper is attached as Appendix 1 (Dennis, R., Farhart, P., Goumas, C. and Orchard, J. (2003). Bowling workload and the risk of injury in elite cricket fast bowlers. *Journal of Science and Medicine in Sport, 6*(3), 359-367).

B1.1 Introduction

As outlined in section A2.11 in the Literature Review, previous research has found that a combination of factors may predispose a bowler to injury: overuse (in terms of bowling volume), poor technique and poor physical preparation [54, 67, 71]. However, prior to preliminary investigations conducted with the New South Wales state cricket squad in 1999-00 [42, 71], no reported research had examined the relationship between the total bowling workload of fast bowlers and the injuries they had sustained.

Guidelines have long been proposed suggesting that the bowling workload of adult fast bowlers (aged over 19 years) should be limited to three spells of six overs per match and participation in three one-hour training sessions per week [40]. However, these recommendations are not based on any solid evidence.

The primary aim of this prospective cohort study was to investigate the relationship between fast bowling workload and the occurrence of overuse-type injury in first-class cricketers. This study is vital to progress injury prevention strategies in cricket. The results of this study will increase the understanding of bowling workload as a risk factor for injury and will provide information that is essential for the development of evidence-based injury prevention guidelines for first-class fast bowlers.

B1.2 Methods

B1.2.1 Recruitment of bowlers

Cricket Australia is the administering body for cricket in Australia. It is comprised of six member associations from each of the Australian states: New South Wales, Queensland, South Australia, Tasmania, Victoria and Western Australia. The six state associations oversee a range of formal cricket programs, ranging from elite competitions to school and club cricket. Each of these state associations was approached and agreed to participate in this study.

To ensure participants in this study were of a similar skill level, only those players selected in the state cricket squads were eligible to participate. Each state association selects one state cricket squad comprised of approximately 25 players (including batsmen, bowlers and wicketkeepers), who are the state's best cricket players. A ‘squad member’ was defined as any player under contract to one of the state associations or a player who took part in a match for the state association during the 2000-01, 2001-02 and/or 2002-03 summer cricket seasons [38]. The state squad coaches were asked to identify those players within the squad that were fast bowlers. Funding was obtained to monitor all six states (and therefore 100% of first-class fast bowlers) in the first two seasons and to continue to monitor three states (approximately 40% of first-class fast bowlers) for the third season.

Ninety-five male fast bowlers were identified by the state squad coaches and all agreed to participate in this study. Bowlers were observed for the duration of the 2000-01, 2001-02 and/or 2002-03 cricket seasons. The number of bowlers who were monitored each season from the six state associations is presented in Table 1. This number of participants was dependent on the number of fast bowlers the state cricket associations chose for the state squads each season. This fluctuated from season to season, depending on factors such as the requests of the coaching staff or the number of fast bowlers who had retired in the previous season. Of the 95 bowlers who participated in the study, 16 were monitored for all three seasons (16 bowlers x 3 seasons = 48 player seasons), 43 were monitored for two seasons only (43 bowlers x 2 seasons = 86 player seasons), and 36 were monitored for one season only (36 bowlers x 1 season = 36 player seasons). Therefore a total of 170 player seasons were recorded. Table 2 shows the number of bowlers from each state association who participated and the total number of player seasons they contributed to the study. The number of bowlers who participated in the study and the age of the bowlers at the start of each season are presented in Table 3.

Table 1 The number of first-class fast bowlers from each of the six state squads participating in the study during the 2000-01, 2001-02 and 2002-03 seasons

State Squad	2000-01	2001-02	2002-03
New South Wales	10	14	8
Queensland	13	11	11
South Australia	10	12	0
Tasmania	9	16	0
Victoria	9	10	10
Western Australia	14	13	0
Total	65	76	29

Table 2 The total number of first-class fast bowlers from each of the six state squads participating in the study and the total number of player seasons they contributed

State Squad	Total number of bowlers participating in the study	Total number of player seasons
New South Wales	17	32
Queensland	16	35
South Australia	13	22
Tasmania	16	25
Victoria	15	29
Western Australia	18	27
Total	95	170

Table 3 The total number of first-class fast bowlers participating in the study and the mean age of the bowlers at the start of each season

Season	Number of bowlers participating	Mean age (SD) in years	Age range
2000-01	65	26.6 (4.0)	18.2 – 36.6
2001-02	76	26.2 (4.4)	17.2 – 37.6
2002-03	29	25.3 (3.7)	19.4 – 32.7

An information statement was issued to the bowlers that outlined the procedures of the project. Bowlers were assured that all personal details would remain confidential, any identifiable information would be kept in secure storage and that the final report would not identify individual bowlers. Bowlers were asked for their written consent to participate and informed that they were able to withdraw from the study at any time without any adverse consequences. This study was approved by Cricket Australia (Appendix 4). The information statement and consent form are attached as Appendix 5.

B1.2.2 Assessing bowling workload

Daily bowling workload in match and training sessions was recorded for the 2000-01, 2001-02 and 2002-03 cricket seasons. For the first season, workload from September 2000 to April 2001, inclusive was recorded for 65 bowlers. For the second season, workload from September 2001 to April 2002, inclusive was recorded for 68 bowlers. During 2001, the Australian national team also participated in a series of matches in England. Therefore, for the second season, workload from May 2001 to April 2002 inclusive, was recorded for the 8 bowlers in the national team. For the third season, workload from September 2002 to April 2003 inclusive, was recorded for 29 bowlers.

Bowling workload was assessed in terms of the frequency of bowling (measured in days) and the type of bowling performed (match or training). To quantify total seasonal bowling workload, it was necessary to monitor the national squad, state squad and club training sessions, as well as any matches the bowlers participated in throughout the season. These matches included fixtures in the following competitions: Pura Cup, ING Cup, ACB Cup, Grade Competitions, Orange Test Series, VB One-Day Series, Ashes Series, as well as tour and promotional matches. The number of matches that each bowler participated in depended on whether the relevant state or national selection panels included them in the team for each individual match.

The methods of data collection to assess training bowling workload used in this study were adapted from those previously developed in a pilot study led by the author of this thesis [46, 105]. Video surveillance of state squad training sessions was found to be an accurate method of assessing training bowling workload in the pilot study, however it was also determined to be expensive and time consuming if used in six locations as required in the present study. Informal feedback from state associations also suggested that they did not have the resources to be responsible for the operation of the video camera. As the footage was only used to determine the number of deliveries being bowled on each training day, it was decided that video surveillance was not necessary and that workload could be accurately determined by someone attending and observing the training sessions. Therefore, a research assistant was employed in each of the six states to attend and observe every state squad training session throughout the 2000-01, 2001-02 and 2002-03 seasons. When players were required to travel interstate for Pura Cup or ING Cup matches, the research assistant employed in that state monitored training sessions. The scorer for the Australian team kept a record of national squad training deliveries for bowlers who were selected in the Australian One-day and Test squads.

It was expected that bowlers would participate in a limited number of training sessions for their grade cricket clubs throughout the season due to competing commitments to their state squad. Bowlers were asked to keep a record of the number of deliveries they bowled per day at grade club training sessions and to provide this information to the research assistant attending the state squad training sessions. All of the bowlers in this study provided information to the research assistant regarding any bowling completed at grade club training on a weekly basis. The grade club training logbook used is attached as Appendix 6. The number of deliveries bowled on each training day was entered into a Microsoft ACCESS database.

Daily match bowling workload was determined from the fixture scorecards. These scorecards routinely record information about the number of overs bowled, wickets taken, maiden overs bowled and runs scored against each bowler. For this study, it was only necessary to obtain details of the number of overs bowled per match day. The majority of match scorecards were available on the internet, on the Cricket Australia or state cricket association websites. These scorecards were accessed online and information for study participants retrieved and entered into the ACCESS database. The state cricket associations provided hard copies of any match scorecards not available on the internet. Scorecards for 100% of the scheduled matches in all three seasons were obtained either electronically or in hard copy format.

It is usual practice for players to complete a warm-up session at the commencement of each match day. An estimate of 18 deliveries per bowler was recorded as the warm-up component for each match day played for the duration of the season, as per previous research [42]. After consultation with the coach of the Australian Test and one-day squads, it was decided to record an estimate of 8 deliveries per bowler as the warm-up prior to each match day for bowlers selected in the national team.

B1.2.3 Injury surveillance

Information pertaining to injury incidence, nature and severity was obtained from an injury surveillance system implemented by Cricket Australia and administered by team doctors and physiotherapists appointed to each of the state and Australian squads [105].

The injury surveillance system recorded information about the date, cause, site and nature of the injury in addition to information regarding treatment received for the injury. Diagnosis, mechanism and cause of injury were determined through collaboration between the team doctor and physiotherapist. Injury diagnosis was coded in a cricket-specific modification of OSICS [143]. The mechanism of injury field included options such as a collision with another player; being hit by the ball; pushing off to run; gradual bowling; gradual running; slipping or tripping. The definition of injury used in the Cricket Australia injury surveillance system, and adopted in the present study, was described previously in section A2.9.

The matches under consideration in this injury survey, defined as major matches, were all Test matches and one-day international matches involving the Australian squad and all domestic first-class matches (Pura Cup) and domestic one-day matches (ING Cup) involving any of the six state squads. Unless an injury met any of the specified criteria, an injury that occurred during training or grade cricket was not included in this study.

A measure of injury severity was not included in this study for a number of reasons: differences in the rehabilitation practices of the sports medical staff associated with each state team; variable pain tolerances between bowlers; and non-uniform scheduling of major matches.

The coordinator of the injury surveillance system provided information pertaining to the injuries sustained by the bowlers in this study to the author of this thesis. The details of each injury were reviewed by the coordinator of the injury surveillance system (Dr John Orchard, a sports physician with 5 years of experience working with cricketers) and a sports physiotherapist (Patrick Farhart, with 10 years of experience working with cricketers), who were both recognised experts in the field of cricket injury. Those injuries that were attributed to the repetitive microtrauma associated with fast bowling were included in this study. Since the primary aim of this study was to identify risk factors for repetitive microtrauma injuries, collision-type injuries, such as colliding with another player, were excluded. Whilst every effort was made to include only those injuries that were a result of the repetitive stress of fast bowling during the study period, it is acknowledged that the pathogenesis of some of these injuries may be attributed to other causes, including the consequences of incomplete recovery from a previous injury.

Injury in the previous season was considered a potential risk factor for sustaining a bowling-related injury in the subsequent season. The injury data provided during the 2000-01, 2001-02 and 2002-03 seasons was used to determine whether bowlers who had sustained a bowling-related injury in the previous season were at an increased risk of sustaining another bowling-related injury in the subsequent season. Injury data for the 1999-00 season was also obtained from the injury surveillance system [42] for bowlers who participated in the first season of this workload study.

B1.2.4 Statistical procedures

The main outcome measure of interest in this study was repetitive microtrauma injury (for the purpose of brevity hereafter referred to as 'injury', unless otherwise specified), which was coded as a yes/no variable in SPSS. The risk factors that were investigated using univariate analysis in this study were:

- injury in the previous season;
- age at start of the season;
- number of days between bowling occurrences;
- number of bowling days per week;

- number of deliveries per bowling day; and
- number of deliveries bowled per week.

To describe the relationship between workload and injury, comparisons of bowling workload were made between injured and uninjured bowlers. To increase the sample size, the datasets for each season (2000-01, n = 65 bowlers; 2001-02, n = 76 bowlers; and 2002-03 season, n = 29 bowlers) were combined and pooled results are reported (n = 170 bowlers). Analyses investigating the relationship between bowling workload and injury were conducted for each of the following measures of bowling workload:

- combined workload (match plus training);
- match workload only;
- training workload only; and
- training workload as a proportion of combined workload.

The bowling workload measure "training workload as a proportion of combined workload" was a number between 0 and 1, calculated using the following formula:

Equation 1 Formula used to calculate training workload as a proportion of combined workload

$$Training\ workload\ proportion = \frac{Training\ workload}{(Training\ workload + Match\ workload)}$$

For bowlers who were uninjured, total bowling workload for the duration of each season was calculated. However, for bowlers who sustained an injury during a season, only bowling completed prior to the occurrence of injury was calculated. This was based on the consideration that bowling behaviour may change significantly after injury, particularly if the player is unable to bowl for a lengthy period of time. Since the primary aim of this study was to investigate workload as risk factor for injury, it was important to differentiate the injury risk factors from the injury sequelae [109].

If a bowler sustained multiple injuries or recurrences of an injury within a season, only the workload prior to the first injury occurrence each season has been reported. As players may not bowl for a period of time following injury or may change their bowling behaviour once an injury has been sustained, it was decided to restrict workload and injury analysis to the first injury alone.

When calculating the average weekly workload of individual bowlers, only those weeks in which the player bowled were included. This was to ensure that the mean number of deliveries would not be influenced by periods of inactivity due to training sessions and matches not being scheduled during some periods (eg. the Christmas holiday period).

Comparisons between the injured and uninjured bowlers groups were conducted in SPSS (Chicago, Illinois, USA) using independent t-tests and Mann-Whitney U tests for parametric and non-parametric data respectively. For parametric data, the mean score of the continuous risk factor variables for the injured group was compared with the mean of the uninjured group. For non-parametric data, the median score of the continuous risk factor variables was compared [40]. For these statistical tests, the 5% level of significance was used ($p<0.05$).

Each continuous risk factor variable was categorised into quintiles (except “training workload as a proportion of combined workload” which was categorised into tertiles), for comparison with the outcome of injury. This categorisation was done to improve the practical interpretation of the results. For example, showing that risk of injury increases as workload increases does not identify a point at which intervention is appropriate. Whereas demonstrating a difference between the group with an average workload and the group with the highest/lowest workload provides a clear indication of who is at greatest risk of injury. The cut-points for categorising the continuous variables into groups were rounded to the nearest appropriate number. For example, the exact quintiles of 2.1, 2.4, 2.8 and 3.3 days for the workload variable “mean number of bowling days per week” were rounded to 2.0, 2.5, 3.0 and 3.5 days. Whereas the exact quintiles of 120.7, 141.1, 166.6 and 192.9 deliveries for the workload variable “mean number of deliveries bowled per week” were rounded to 125, 150, 175 and 200 deliveries. This was done to ensure that any workload recommendations arising from this research could be easily applied in a practical setting. This rounding of the cut-points had minimal impact on the data. For example, for the variable “mean number of deliveries bowled per week”, the distribution of bowlers into the five groups, according to the rounded quintiles was 26.2%, 19.5%, 22.0%, 17.7%, and 14.6%. Whereas for the exact quintiles, there would have been 20% of bowlers in each group. Therefore, by rounding the cut-points, the distribution of bowlers in the five workload groups did not change substantially.

The risk of injury, relative to the chosen reference category (denoted as ‘Ref’), was assessed through the calculation of a risk ratio (RR) [46]. To allow the identification of a non-linear relationship between the proposed risk factors and injury, the middle category was chosen as the reference group. The RR was calculated as the ratio of risks within a given period of a group with the risk factor present (numerator) compared with a group with the risk factor absent (denominator), using the formula below:

Equation 2 The formula used to calculate risk ratios

$$RR = \frac{a/(a+b)}{c/(c+d)}$$

where *a* = bowlers with the risk factor present that were injured, *b* = bowlers with the risk factor present that were uninjured, *c* = bowlers with the risk factor absent that were injured and *d* = bowlers with the risk factor absent that were uninjured. RRs and confidence intervals were estimated using the Crosstab procedure in SPSS. Those RRs for which the 95% confidence intervals did not include 1.0 were considered significant.

Anecdotally, some cricket coaches have suggested that it is possible to estimate combined bowling workload (match + training) based on match workload only, for a group of fast bowlers. If possible, this would remove the need to monitor all training sessions and the number of deliveries bowled at training, which is seen by some as an expensive and time-consuming exercise.

To assess whether combined workload could be predicted from match workload only, linear regression (x = match workload; y = combined workload) was used to forecast total workload (prior to any injury) from total match workload only (prior to any injury) in Microsoft Excel. This linear regression equation was then compared with the actual workload recorded in this study to determine how closely combined bowling workload (dependent variable y) can be predicted from match workload only (independent variable x).

B1.3 Results

B1.3.1 Injury occurrence

The number of injured bowlers and the percentage of all participants that were injured each season are presented in Table 4.

Table 4 The number of first-class fast bowlers who were injured each season and the percentage of all study participants that were injured

Season	Number of injured bowlers	Percentage of all participants that were injured
2000-01	38	58.5
2001-02	46	60.5
2002-03	14	48.3

There were differing levels of severity of these injuries. However, as per the injury inclusion criteria listed in section A2.9, all injuries limited or prevented participation in at least one major match.

It is beyond the scope of this thesis to investigate the timing of, severity or the medical details, of these injuries. However to provide an overview, Table 5 lists the frequency of repetitive microtrauma injuries reported in this study according to the OSICS cricket-specific injury categories recorded in the Cricket Australia injury surveillance system [144].

Table 5 The frequency of bowling-related injuries reported by first-class fast bowlers according to the OSICS cricket-specific injury categories

Body region	OSICS injury category	Number of injuries (% of total)
Head and neck	Neck injuries	1 (1.0%)
Upper limb	Shoulder tendon injuries	4 (4.1%)
	Shoulder instability	2 (2.0%)
	Elbow injuries	1 (1.0%)
Trunk and back	Side and abdominal strains	16 (16.3%)
	Lumbar injuries (other than stress fractures/reactions)	12 (12.2%)
	Lumbar stress fractures/reactions	9 (9.2%)
	Rib stress fractures	2 (2.0%)
	Other trunk injuries	1 (1.0%)
Lower limb	Hamstring strain injuries	11 (11.2%)
	Groin injuries	8 (8.2%)
	Calf muscle strain injuries	5 (5.1%)
	Foot stress fractures	5 (5.1%)
	Knee cartilage injuries	5 (5.1%)
	Quadriceps strain injuries	5 (5.1%)
	Heel and achilles injuries	3 (3.1%)
	Knee tendon injuries	3 (3.1%)
	Ankle and foot sprains	1 (1.0%)
	Knee ligament injuries	1 (1.0%)
	Leg stress fractures	1 (1.0%)
	Other lower limb injuries	1 (1.0%)
	Shin splints/compartment syndrome	1 (1.0%)

B1.3.2 Injury in the previous season as a risk factor for injury

Bowlers who had sustained a bowling-related injury in the previous season were not at a significantly increased risk of sustaining a bowling-related injury in the subsequent season, when compared with those injured bowlers who had not sustained an injury in the previous season. The RRs for each of the three seasons are shown in Table 6.

Table 6 Injury in the previous season as a risk factor for sustaining a bowling-related injury in the subsequent season for first-class fast bowlers

Season	% of injured bowlers who were also injured in the previous season	% of uninjured bowlers who were injured in the previous season	RR as compared with injured bowlers who were not injured in the previous season	95% CI
2000-01	34.2	29.6	1.09	0.71, 1.66
2001-02	75.0	46.7	1.50	0.93, 2.42
2002-03	80.0	50.0	2.29	0.63, 8.25

B1.3.3 Age at the start of the season as a risk factor for injury

There was no difference in the mean age at the start of the season for injured and uninjured bowlers (mean: 26.5 and 25.8 years respectively, t = 1.136, df = 168, p = 0.258). The risk of injury according to age was calculated using bowlers aged between 25.0 and 26.9 years as the reference group. Bowlers younger or older than those in the reference group were at a significantly reduced risk of injury, as shown in Table 7.

Table 7 Age at the start of the season as a risk factor for injury to first-class fast bowlers

Age at start of the season (years)	% of injured bowlers in this age group	% of uninjured bowlers in this age group	RR	95% CI
< 22.0	15.3	20.8	0.59	0.40, 0.87
22.0 – 24.9	20.4	29.2	0.57	0.40, 0.81
25.0 – 26.9	23.5	5.6	Ref	
27.0 – 29.9	22.4	23.6	0.66	0.48, 0.91
≥ 30.0	18.4	20.8	0.64	0.45, 0.91

* Significant RRs are shaded

B1.3.4 Number of days between bowling occurrences as a risk factor for injury

In comparing the mean number of days between bowling occurrences, there was no difference between injured bowlers and uninjured bowlers (mean: 3.7 versus 3.4 days respectively). However, the data for the number of days between bowling occurrences did not follow a normal distribution. Therefore, the median values were compared using a Mann-Whitney U test. The median number of days between bowling occurrences were also very similar in injured bowlers and uninjured bowlers (median: 2.9 versus 3.0 days, *M* rank: 78.6 and 88.7 respectively, Mann Whitney U = 2935.5, p = 0.175).

The risk of injury according to the average number of days between bowling occurrences was assessed, using those players with an average of 3.0 – 3.9 days between bowling occurrences as the reference group. As shown in Table 8, bowlers with the least (<2.0) and most (≥ 5.0) number of days between bowling occurrences were at a significantly increased risk of injury.

Table 8 Risk of injury according to the average number of days between bowling occurrences for first-class fast bowlers

Average number of days between bowling occurrences	% of injured bowlers with this workload	% of uninjured bowlers with this workload	RR	95% CI
< 2.0	9.7	0.0	2.27	1.66, 3.11
2.0 – 2.9	44.1	44.4	1.28	0.88, 1.85
3.0 – 3.9	23.7	38.9	Ref	
4.0 – 4.9	9.7	11.1	1.20	0.70, 2.08
≥ 5.0	12.9	5.6	1.71	1.12, 2.60

* Significant RRs are shaded

The association between workload and injury was also investigated for training and match occurrences separately. As shown in Table 9, when considering training workload only, bowlers who had bowled the most frequently (< 5.0 days between training bowling occurrences) were at an increased risk of injury, with the RR approaching significance.

Table 9 Risk of injury according to the average number of days between training bowling occurrences for first-class fast bowlers

Average number of days between training bowling occurrences	% of injured bowlers with this workload	% of uninjured bowlers with this workload	RR	95% CI
< 5.0	25.8	6.9	1.48	0.94, 2.31
5.0 – 5.9	15.7	8.3	1.26	0.76, 2.08
6.0 – 6.9	11.2	11.1	Ref	
7.0 – 7.9	11.2	23.6	0.67	0.35, 1.27
≥ 8.0	36.0	50.0	0.85	0.52, 1.37

When investigating match workload occurrences only, the risk of injury was significantly higher for bowlers who had bowled the most frequently (< 3.0 days between match bowling occurrences), as shown in Table 10.

Table 10 Risk of injury according to the average number of days between match bowling occurrences for first-class fast bowlers

Average number of days between match bowling occurrences	% of injured bowlers with this workload	% of uninjured bowlers with this workload	RR	95% CI
< 3.0	13.8	4.2	1.51	1.01, 2.27
3.0 – 3.9	35.6	35.2	1.05	0.70, 1.55
4.0 – 4.9	20.7	22.5	Ref	
5.0 – 5.9	13.8	16.9	0.94	0.57, 1.57
≥ 6.0	16.1	21.1	0.91	0.56, 1.49

* Significant RRs are shaded

When considering training workload as a proportion of combined workload, there was no difference in the mean proportions of the injured and uninjured bowlers (mean: 0.61 versus 0.63 respectively). However the data did not follow a normal distribution and therefore, the median values were compared using a Mann-Whitney U test. There was also no difference in the median proportions for injured bowlers and uninjured bowlers (median: 0.63 for both groups, *M* rank: 74.0 and 81.6 respectively, Mann Whitney $U = 2654.5$, $p = 0.290$).

However, bowlers with the lowest training workload as a proportion of combined workload (< 0.55) as compared with bowlers in the reference group (0.55 – 0.64) were at a significantly increased risk of injury, as shown in Table 11.

Table 11 Risk of injury for first-class fast bowlers according to training workload as a proportion of combined workload, with respect to the number of days between bowling occurrences

Training workload as a proportion of combined workload	% of injured bowlers with this proportion	% of uninjured bowlers with this proportion	RR	95% CI
< 0.55	34.1	15.7	1.76	1.21, 2.57
0.55 – 0.64	26.8	45.7	Ref	
≥ 0.65	39.0	38.6	1.33	0.89, 1.98

* Significant RRs are shaded

B1.3.5 Number of bowling days per week as a risk factor for injury

The mean number of bowling days per week was the same for injured bowlers and uninjured bowlers (mean = 2.6 for both groups). However, the data for the number of bowling days per week did not follow a normal distribution. Therefore, when comparing the injured and uninjured bowlers, the median values were compared using a Mann-Whitney U test. The median number of bowling days per week was similar in injured bowlers and uninjured bowlers (median: 2.7 versus 2.6 days, *M* rank: 82.9 and 81.9 respectively, Mann Whitney U = 3271.5, p = 0.893).

The risk of injury according to the average number of bowling days per week was assessed using bowlers with an average of 2.5 – 2.9 days per week as the reference group. As shown in Table 12, bowlers with the highest number of bowling days per week (≥ 3.5) were at a significantly increased risk of injury. Bowlers with the lowest number of bowling days per week (< 2.0) were also at an increased risk of injury, with the RR approaching significance.

Table 12 Risk of injury according to the average number of bowling days per week for first-class fast bowlers

Average number of bowling days per week	% of injured bowlers with this workload	% of uninjured bowlers with this workload	RR	95% CI
< 2.0	19.6	8.3	1.44	1.00, 2.07
2.0 – 2.4	21.7	33.3	0.87	0.57, 1.34
2.5 – 2.9	25.0	29.2	Ref	
3.0 – 3.4	18.5	23.6	0.96	0.62, 1.48
≥ 3.5	15.2	5.6	1.49	1.02, 2.17

* Significant RRs are shaded

These trends were consistent when training and match workload were examined separately. Bowlers with the highest number of training bowling days per week (≥ 1.8) and bowlers with the highest number of match bowling days per week (≥ 3.0) were at a significantly increased risk of injury as shown in Tables 13 and 14, respectively.

Table 13 Risk of injury according to the average number of training bowling days per week for first-class fast bowlers

Average number of training bowling days per week	% of injured bowlers with this workload	% of uninjured bowlers with this workload	RR	95% CI
< 1.2	13.3	12.5	1.27	0.77, 2.10
1.2 – 1.3	21.1	33.3	0.98	0.61, 1.59
1.4 – 1.5	20.0	30.6	Ref	
1.6 – 1.7	20.0	15.3	1.38	0.88, 2.15
≥ 1.8	25.6	8.3	1.76	1.19, 2.60

* Significant RRs are shaded

Table 14 Risk of injury according to the average number of match bowling days per week for first-class fast bowlers

Average number of match bowling days per week	% of injured bowlers with this workload	% of uninjured bowlers with this workload	RR	95% CI
< 1.5	18.6	8.5	1.41	0.98, 2.01
1.5 – 1.9	27.9	32.4	0.99	0.68, 1.44
2.0 – 2.4	34.9	39.4	Ref	
2.5 – 2.9	10.5	19.7	0.76	0.43, 1.33
≥ 3.0	8.1	0.0	1.93	1.51, 2.48

* Significant RRs are shaded

When considering training workload as a proportion of combined workload, there was no difference in the mean proportions of the injured and uninjured bowlers (mean: 0.44 versus 0.42 respectively). However the data did not follow a normal distribution and therefore, the median values were compared using a Mann-Whitney U test. There was a small, but insignificant difference in the median proportions for injured bowlers and uninjured bowlers (median: 0.44 and 0.41 respectively, *M* rank: 84.2 and 70.7 respectively, Mann Whitney U = 2461.5, p = 0.062). As shown in Table 15, there was a trend towards a reduced risk of injury for bowlers with the lowest training workload as a proportion of combined workload (< 0.40), as compared with bowlers in the reference group (0.40 – 0.44).

Table 15 Risk of injury for first-class fast bowlers according to training workload as a proportion of combined workload, with respect to the number of bowling days per week

Training workload as a proportion of combined workload	% of injured bowlers with this proportion	% of uninjured bowlers with this proportion	RR	95% CI
< 0.40	28.6	47.1	0.69	0.47, 1.01
0.40 – 0.44	32.1	24.3	Ref	
≥ 0.45	39.3	28.6	1.02	0.74, 1.39

B1.3.6 Number of deliveries per bowling day as a risk factor for injury

There was no difference in the mean number of deliveries per bowling day for injured and uninjured bowlers (mean: 58.0 and 59.6 deliveries respectively, $t = -0.858$, $df = 163$, $p = 0.392$). As shown in Table 16, there was a non-significant trend towards an increased risk of injury for bowlers with the lowest (< 40.0) number of deliveries bowled per day.

Table 16 Risk of injury according to the average number of deliveries per bowling day for first-class fast bowlers

Average number of deliveries per day	% of injured bowlers with this workload	% of uninjured bowlers with this workload	RR	95% CI
< 40.0	8.6	4.2	1.22	0.80, 1.87
40.0 – 49.9	12.9	15.3	0.88	0.56, 1.37
50.0 – 59.9	33.3	29.2	Ref	
60.0 – 69.9	28.0	38.9	0.81	0.57, 1.15
≥ 70.0	17.2	12.5	1.07	0.74, 1.55

These findings were consistent with the trends observed when investigating training workload only, as shown in Table 17. Bowlers with the lowest number of deliveries per training bowling day (< 35.0) were at a significantly increased risk of injury.

Table 17 Risk of injury according to the average number of deliveries per training bowling day for first-class fast bowlers

Average number of deliveries per training day	% of injured bowlers with this workload	% of uninjured bowlers with this workload	RR	95% CI
< 35.0	18.7	5.6	1.50	1.04, 2.15
35.0 – 39.9	22.0	27.8	0.93	0.60, 1.42
40.0 – 44.9	22.0	23.6	Ref	
45.0 – 49.9	15.4	26.4	0.78	0.48, 1.29
≥ 50.0	22.0	16.7	1.16	0.77, 1.73

* Significant RRs are shaded

There was no association between the number of deliveries bowled per match day and risk of injury, as shown in Table 18.

Table 18 Risk of injury according to the average number of deliveries per match bowling day for first-class fast bowlers

Average number of deliveries per match day	% of injured bowlers with this workload	% of uninjured bowlers with this workload	RR	95% CI
< 55.0	11.5	15.5	0.83	0.49, 1.40
55.0 – 64.9	25.3	23.9	0.98	0.67, 1.44
65.0 – 74.9	26.4	23.9	Ref	
75.0 – 84.9	21.8	26.8	0.87	0.57, 1.32
≥ 85.0	14.9	9.9	1.13	0.74, 1.72

When considering training workload as a proportion of combined workload, there was no difference in the mean proportions of the injured and uninjured bowlers (mean: 0.38 versus 0.39 respectively, t = -1.000, df = 154, p = 0.319). Similarly, there was no association with the risk of injury, as shown in Table 19.

Table 19 Risk of injury for first-class fast bowlers according to training workload as a proportion of combined workload, with respect to the number of deliveries per bowling day

Training workload as a proportion of combined workload	% of injured bowlers with this proportion	% of uninjured bowlers with this proportion	RR	95% CI
< 0.35	28.6	18.8	1.15	0.83, 1.58
0.35 – 0.39	40.5	37.7	Ref	
≥ 0.40	31.0	43.5	0.82	0.57, 1.17

B1.3.7 Number of deliveries bowled per week as a risk factor for injury

The mean number of deliveries bowled per week was similar for injured bowlers and uninjured bowlers (mean: 154.7 and 153.6 deliveries respectively). However, the data for the number of deliveries per week did not follow a normal distribution. A Mann-Whitney U test showed that there was no difference between the median number of deliveries per week for injured bowlers and uninjured bowlers (median: 157.9 versus 155.9 deliveries, *M* rank: 82.9 and 82.1 respectively, Mann Whitney U = 3280.0, p = 0.916).

The risk of injury according to the average number of deliveries bowled per week was determined, using bowlers with an average of 150.0 – 174.9 deliveries per week as the reference group. As shown in Table 20, bowlers with the highest number of deliveries per week (≥ 200.0) were at a significantly increased risk of injury. There was also a non-significant increase in the risk of injury for bowlers with the lowest number of deliveries per week (< 125.0).

Table 20 Risk of injury according to the average number of deliveries bowled per week for first-class fast bowlers

Average number of deliveries per week	% of injured bowlers with this workload	% of uninjured bowlers with this workload	RR	95% CI
< 125.0	29.3	22.2	1.33	0.88, 2.01
125.0 – 149.9	17.4	22.2	1.06	0.65, 1.73
150.0 – 174.9	18.5	26.4	Ref	
175.0 – 199.9	15.2	20.8	1.02	0.61, 1.70
≥ 200.0	19.6	8.3	1.59	1.05, 2.41

* Significant RRs are shaded

When considering training and match workload separately, bowlers with the highest number of training deliveries per week were at an increased risk of injury, as were bowlers with the highest number of match deliveries per week. These results, presented in Tables 21 and 22, were only marginally non-significant.

Table 21 Risk of injury according to the average number of training deliveries bowled per week for first-class fast bowlers

Average number of training deliveries per week	% of injured bowlers with this workload	% of uninjured bowlers with this workload	RR	95% CI
< 40.0	4.4	4.2	1.31	0.64, 2.70
40.0 – 49.9	13.3	12.5	1.31	0.80, 2.16
50.0 – 59.9	22.2	36.1	Ref	
60.0 – 69.9	25.6	22.2	1.36	0.89, 2.07
≥ 70.0	34.4	25.0	1.46	0.98, 2.15

Table 22 Risk of injury according to the average number of match deliveries bowled per week for first-class fast bowlers

Average number of match deliveries per week	% of injured bowlers with this workload	% of uninjured bowlers with this workload	RR	95% CI
< 100.0	20.9	16.9	1.32	0.82, 2.12
100.0 – 124.9	18.6	18.3	1.21	0.74, 2.00
125.0 – 149.9	17.4	25.4	Ref	
150.0 – 174.9	18.6	26.8	1.01	0.60, 1.69
≥ 175.0	24.4	12.7	1.54	0.99, 2.39

When considering training workload as a proportion of combined workload, there was no difference in the mean proportions of the injured and uninjured bowlers (mean: 0.38 versus 0.39 respectively, t = -1.000, df = 154, p = 0.319). Similarly, there was no association between training workload as a proportion of combined workload and risk of injury, as presented in Table 23.

Table 23 Risk of injury for first-class fast bowlers according to training workload as a proportion of combined workload, with respect to the number of deliveries bowled per week

Training workload as a proportion of combined workload	% of injured bowlers with this proportion	% of uninjured bowlers with this proportion	RR	95% CI
< 0.30	40.2	49.3	0.84	0.58, 1.21
0.30 – 0.34	26.8	22.5	Ref	
≥ 0.35	32.9	28.2	0.99	0.69, 1.43

B1.3.8 Predicting total seasonal workload from match workload only

Linear regression was used to forecast total workload (prior to any injury) from total match deliveries (prior to any injury) only, for all bowlers. This linear regression equation was then compared with the actual number of total deliveries bowled (as recorded in this study) to determine how closely total bowling workload (dependent variable *y*) can be predicted from match workload only (independent variable *x*) for a group of fast bowlers.

Figure 8 shows the prediction of total deliveries from match deliveries only and Figure 9 shows the prediction of total sessions from match sessions only, using combined data from the three seasons. As can be seen in these figures, the total deliveries and total sessions are strongly correlated with the match deliveries and match sessions, respectively. However, as shown in Table 24, the *y*-intercepts of the linear regression equations do not equal zero and they differ considerably for each individual season. For example, the *y*-intercept for the season 2000-01 was 820 deliveries. This is significantly different to the *y*-intercepts for the other two seasons, as the value for 2000-01 did not lie within the 95% CIs for the 2001-02 and 2002-03 seasons, as shown in Table 24. The *y*-intercepts are important as they provide information regarding the number of deliveries or sessions that needed to be added to the workload determined by the slope of the line of best fit. For example, the total number of deliveries during the 2000-01 season was equal to 1.11*x* (where *x* = total match deliveries) plus the y-intercept of 820 deliveries.

Figure 8 – Predicting total deliveries prior to injury (if any) from match deliveries only, for the 2000-01, 2001-02 and 2002-03 seasons combined

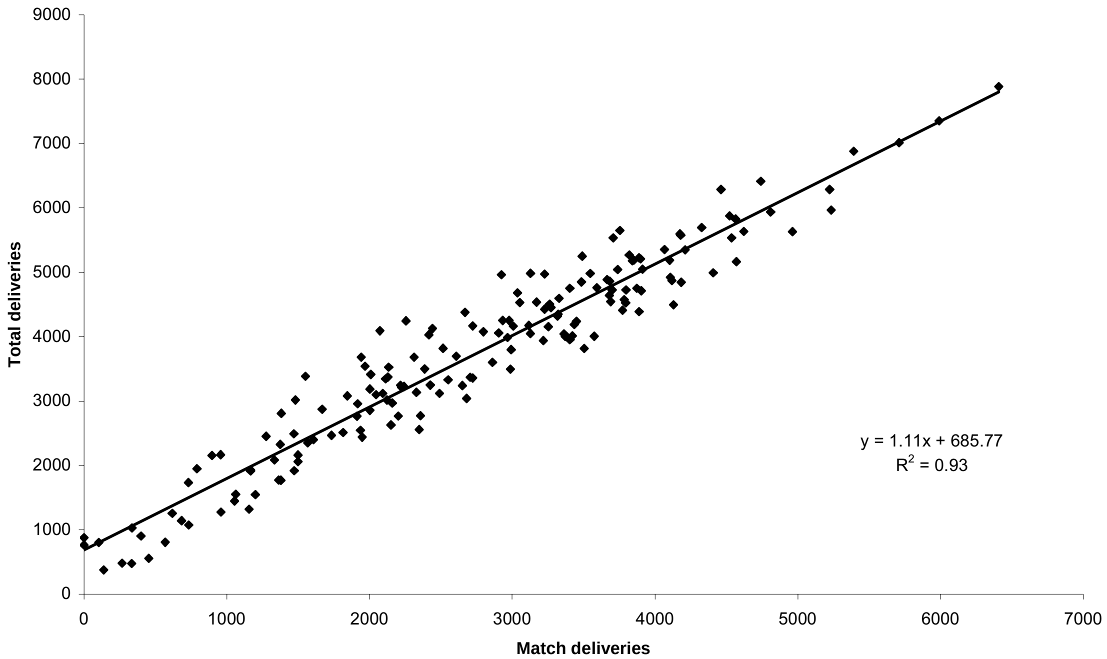


Figure 9 – Predicting total sessions prior to injury (if any) from match sessions only, for the 2000-01, 2001-02 and 2002-03 seasons combined

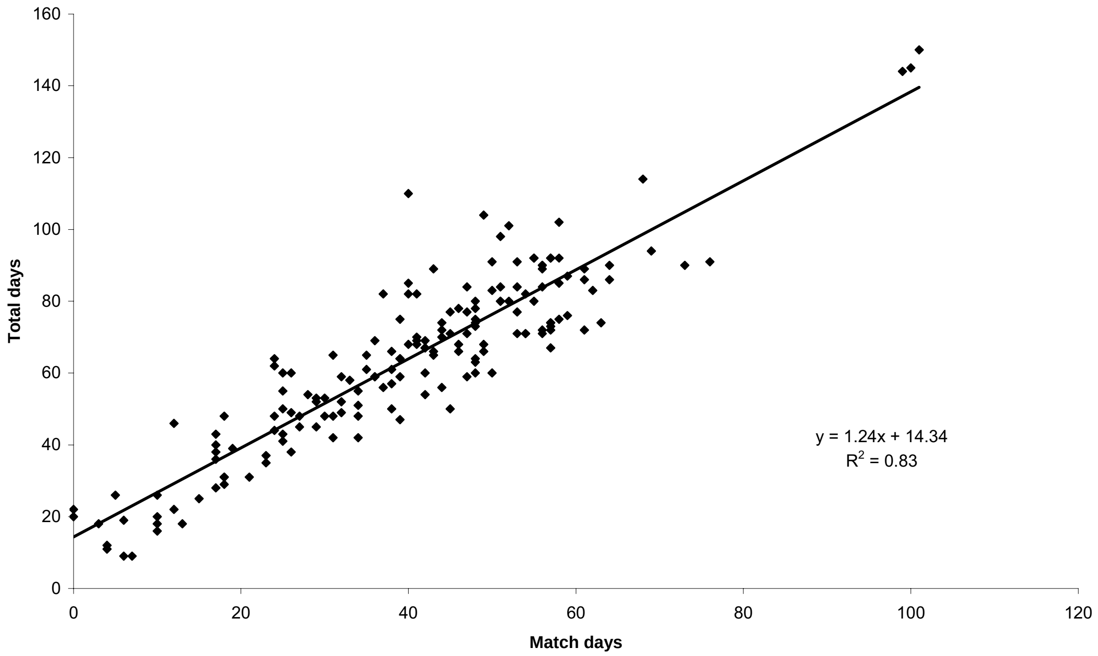


Table 24 Linear regression equations for predicting total deliveries prior to injury (if any) from match deliveries only

Season	Slope, *m* (where *x* = total match deliveries)	95% CI for *m*	y-intercept, *b* (deliveries)	95% CI for *b*	R square
All seasons combined	1.11x	1.06, 1.16	686	541, 831	0.93
2000-01	1.11x	1.02, 1.21	820	530, 1110	0.90
2001-02	1.12x	1.10, 1.21	612	448, 775	0.96
2002-03	1.03x	0.96, 1.09	546	339, 753	0.98

Table 25 Linear regression equations for predicting total sessions prior to injury (if any) from match sessions only

Season	Slope, *m* (where *x* = total match sessions)	95% CI for *m*	y-intercept, *b* (sessions)	95% CI for *b*	R square
All seasons combined	1.24x	1.16, 1.33	14	11, 18	0.83
2000-01	1.33x	1.18, 1.49	13	6, 19	0.83
2001-02	1.34x	1.23, 1.45	13	9, 18	0.90
2002-03	1.02x	0.90, 1.14	14	8, 20	0.91

B1.4 Summary of results

Listed below are the significant findings identified in this study:

Age

- Bowlers aged < 25.0 years or ≥ 27.0 years were at a significantly reduced risk of injury, as compared with bowlers aged 25.0 – 26.9 years.

Combined workload (match + training)

- Risk of injury was significantly increased for bowlers with the least (< 2.0) and most (≥ 5.0) number of days between bowling occurrences, as compared with bowlers with an average of 3.0 – 3.9 days between bowling occurrences.

- Bowlers with the lowest training workload as a proportion of combined workload (< 0.55) as compared with bowlers in the reference group (0.55 – 0.64) were at a significantly increased risk of injury.

- Bowlers with the highest number of bowling days per week (≥ 3.5) were at a significantly increased risk of injury, as compared with bowlers with an average of 2.5 – 2.9 bowling days per week.

- Bowlers with the highest number of deliveries per week (≥ 200.0) were at a significantly increased risk of injury as compared with bowlers with an average of 150.0 – 174.9 deliveries per week.

Match workload only

- Risk of injury was significantly increased for bowlers who had bowled the most frequently (< 3.0 days between match bowling occurrences), as compared with bowlers with an average of 4.0 – 4.9 days between match bowling occurrences.

- Bowlers with the highest number of bowling days per week (≥ 3.0) were at a significantly increased risk of injury, as compared with bowlers with an average of 2.0 – 2.4 match bowling days per week.

Training workload only

- Bowlers with the highest number of bowling days per week (≥ 1.8) were at a significantly increased risk of injury, as compared with bowlers with an average of 1.4 – 1.5 training bowling days per week.

- Bowlers with the lowest number of deliveries per training bowling day (< 35.0) were at a significantly increased risk of injury as compared with bowlers with an average of 40.0 – 44.9 deliveries per training bowling day.

B2: Bowling workload and the risk of repetitive microtrauma injury to adolescent fast bowlers

This chapter describes the results obtained from the workload and injury study conducted with adolescent fast bowlers during the 2002-03 season. The material in this chapter has already been published in a peer-review journal and a copy of this paper is attached as Appendix 2 (Dennis, R.J., Finch, C.F. and Farhart, P.J. (2005). Is bowling workload a risk factor for injury to Australian junior cricket fast bowlers? *British Journal of Sports Medicine, 39*(11), 843-846).

B2.1 Introduction

The results of the previous chapter (B1) demonstrated that bowling workload was significantly associated with injury to adult first-class fast bowlers. However, anecdotally it has been suggested that many adolescent fast bowlers also sustain injuries that either prevent them from further participation in fast bowling or continue to cause difficulties throughout their playing careers. Therefore, it is vital that appropriate injury prevention strategies are also established for adolescent cricketers.

As outlined in the Literature Review, adolescent athletes may be more susceptible to repetitive microtrauma injuries as compared with adults, because the musculoskeletal systems of adolescents are not fully developed [29, 145]. The vulnerability of adolescent cricketers to injury was recognised by Cricket Australia as long ago as the early 1990's, when they developed a Junior Cricket Policy [144]. This policy described bowling workload guidelines for adolescent fast bowlers and outlined the maximum number of deliveries to be bowled in matches and training sessions for those players aged < 19 years [46]. However, analysis of data collected in the first season of the study conducted with first-class fast bowlers (the final results of which are presented in Chapter B1) raised concerns about the appropriateness of the fast bowling workload guidelines for adolescent bowlers that were based on best practice rather than scientific evidence. This was because in some cases, adolescent bowlers were permitted to bowl more than the research suggested was appropriate for adult fast bowlers, as shown in Table 26.

Therefore, the primary aim of this prospective cohort study was to investigate bowling workload as a risk factor for injury to adolescent fast bowlers. A secondary aim was to determine if adolescent bowlers were exceeding the maximum number of deliveries outlined in the current bowling workload guidelines. It is essential that injury prevention guidelines that are specific to adolescent fast bowlers are established, as direct extrapolation from the research conducted with adult first-class fast bowlers may not be appropriate due to the physical, growth-related differences in adolescent athletes.

Table 26 Current workload guidelines for junior fast bowlers compared with the recommendations from research conducted with adult first-class fast bowlers

Age group (years)	Number of deliveries per match innings	Number of training sessions per week	Number of deliveries per training session	Maximum sessions per week	Maximum deliveries per week
Under 13	48	2	30	3	108
Under 15	60	2	36	3	132
Under 17	96	3	36	4	204
Under 19	120	3	42	4	246
First-class *	N/A	1	40	3	188

* Findings from research conducted with fast bowlers of mean age 27 years, as described in Chapter B1 of this thesis. All other data from Cricket Australia's Junior Cricket Policy [46].

B2.2 Methods

B2.2.1 Recruitment of bowlers

As described in Chapter B1, the six state member associations of Cricket Australia oversee a range of formal cricket programs, ranging from elite competitions to school and club cricket. One of the programs coordinated by Cricket NSW is the NSW Districts Cricket Association. This association is comprised of a number of district/shire associations in New South Wales and each district consists of a number of clubs. The associations cater for both junior and senior cricket players to take part in intra-district and inter-district (representative) competitions. One of these associations, the Sutherland Shire Junior Cricket Association (SSJCA), was approached to participate in this study and agreed to take part.

In addition to the six state member associations of Cricket Australia, there are two non-member territory associations, including ACT Cricket which is the administering association for cricket in the Australian Capital Territory. This association also oversees a range of community level and elite cricket programs for both junior and senior cricket players. The High Performance Department of ACT Cricket agreed to participate in this study.

To ensure that the study participants were of a similar skill level, ACT Cricket and SSJCA were asked to identify current fast and fast-medium bowlers aged 12 – 18 years who had participated in their high performance representative cricket programs in the previous season. The age criteria was set so that the results of the study could be compared with the current NPBP recommendations for adolescent players [29].

The bowlers participating in this study were part of a larger prospective cohort study being conducted by Cricket Australia and the Australian Institute of Sport (AIS). The project was approved by the Australian Institute of Sport Human Research Ethics Committee (Appendix 7). This larger study recruited both adolescent and adult fast bowlers, who underwent a range of physiological and biomechanical testing at the AIS. The sample size for the larger study from which all of the adolescent participants were recruited for this bowling workload study, was largely determined by the resources required to complete the comprehensive testing protocols. For the larger Cricket Australia and AIS study, the maximum sample size was 48 adolescent fast bowlers.

Due to their proximity to the AIS (therefore reducing travel costs associated with the larger Cricket Australia and AIS study), bowlers from the ACT were first recruited into the study. The cricket association in the ACT contacted bowlers who had been members of the Under 15, Under 16 or Under 17 years high performance squads during the 2001-02 season and provided them with an information statement and consent form (Appendix 8). All 16 ACT bowlers agreed to participate in the project. The SSJCA contacted 8 clubs within their association and asked them to identify bowlers who had been selected in representative squads. The SSJCA clubs then provided these bowlers with the project information statement and the first 32 bowlers to agree to participate were recruited into the study (who along with the 16 ACT bowlers comprised the maximum sample of 48 bowlers). Information sessions were held in both Sydney and Canberra for bowlers and their parents/guardians. One bowler did not attend the information session and later refused to participate in the study; by which time it was not possible to recruit another bowler to the study. Therefore 31 bowlers were recruited from SSJCA and 16 bowlers from ACT Cricket. All bowlers, along with their parent or guardian, provided written consent to participate in the project.

B2.2.2 Assessing bowling workload

Daily bowling workload in match and training sessions was recorded for the 2002-03 cricket season. As with the study described in Chapter B1, bowling workload was assessed in terms of the frequency of bowling (measured in days) and the type of bowling performed (match or training). The methods of bowling workload data collection used in this study were adapted from those described in Chapter B1. As the bowlers participating in this study were recruited from 18 different clubs, it was not feasible within the research budget to employ research assistants to monitor club training sessions for each of the

18 locations. Therefore, bowlers were asked to complete a logbook for both match and training bowling workload. Participants completed daily bowling logbooks, attached as Appendix 9, and recorded the number of training, match and pre-match warm-up deliveries bowled each day throughout the season, from October 2002 to March 2003 inclusive. This logbook was forwarded to the author of this thesis on a weekly basis and entered into a central Microsoft ACCESS database. Bowling completed in organised one or two-day matches was categorised as match workload. This included matches for club, school and representative teams. The number of matches that each bowler participated in depended on whether they were selected in the team for each individual match. Training workload included bowling completed during formal training sessions and cricket specific personal training.

To determine the validity of the data collected in bowling logbooks, research assistants attended a number of match and training sessions to independently monitor the number of deliveries that were bowled by participants in this study. Bowlers were informed prior to the commencement of the study that a member of the research team would attend a selection of sessions throughout the season to monitor the number of deliveries bowled. The bowlers were told that this information would be used to validate the data recorded in the bowling logbooks. However, they were not told which sessions would be attended, or who would be attending them. In NSW, the research assistant was a member of the research team that the participants in the study had not previously met. The research assistant in the ACT was an assistant to the high performance coaching staff and regularly attended training sessions and matches in this role.

It was not possible to randomly select the sessions that would be monitored at the start of the season, as match and training schedules were liable to change throughout the course of the season. Also, the attendance of bowlers at these sessions depended on factors such as team selection and their availability to attend sessions. Therefore, the research assistants were asked to keep in regular contact with the coaching staff to determine confirmed dates of sessions and to attend both match and training sessions throughout the season for as many of the participants in the study as possible. A total of 25 training sessions and 25 match sessions were validated throughout the course of the season.

B2.2.3 Injury surveillance

The definition of injury used in this study was adapted from that previously used in the research with first-class fast bowlers [29, 89]. An injury was therefore defined as a condition or illness that:

- affected availability for team selection in a match; and/or
- required surgery at any stage of the year; and/or
- during a match:
    - caused a team member to be absent from the field for greater than one hour; or
    - caused a bowler to finish bowling due to injury before the end of a normal over; or
    - prevented a bowler from being available to bowl during a match.

Bowlers were asked to report any condition or injury, even if it was unrelated to cricket, in their logbooks. A list of reported injuries was prepared on a fortnightly basis throughout the season. This list was then given to a sports physiotherapist, who contacted each bowler to determine the date, cause, site, nature and mechanism of injury as well as to determine if the injury met the inclusion criteria. Injury diagnosis was coded in a cricket-specific modification of the OSICS system [66]. The mechanism of injury field included options such as a collision with another player, being hit by the ball, pushing off to run, gradual bowling, gradual running, slipping or tripping. As part of the larger cohort study, all bowlers underwent a MRI scan at the start of the season and immediately after any back/trunk injury. The results of the post-injury scan were used by the sports physiotherapist to confirm the injury diagnosis for this study. Whilst MRI may not be the most sensitive radiological modality for diagnosis of lumbar bone stress injury [146], it was chosen because of the radiation exposure issues to adolescents associated with CT scan or bone scan [146].

As with the research presented in Chapter B1, injuries included in the analysis were repetitive microtrauma injuries as a result of gradual bowling. Therefore, all injuries had an insidious onset caused by repetitive episodes of microtrauma. Collision-type injuries, such as colliding with another player, were excluded. Unless they met any of the listed criteria, injuries that occurred during training or which only affected participation in training sessions, were not included in the analysis.

B2.2.4 Statistical procedures

The procedures used in the statistical analysis were similar to those described in Chapter B1. The main outcome measure of interest in this study was repetitive microtrauma injury (for the purpose of brevity hereafter referred to as 'injury', unless otherwise specified), which was coded as a yes/no variable in SPSS. The risk factors investigated in this study were:

- age at start of the season;
- number of days between bowling occurrences;
- number of bowling days per week;
- number of deliveries per bowling day; and
- number of deliveries bowled per week.

To describe the relationship between workload and injury, comparisons of bowling workload were made between injured and uninjured bowlers. Analyses investigating the relationship between bowling workload and injury were conducted for each of the following measures of bowling workload:

- combined workload (match plus training);
- match workload only;
- training workload only; and
- training workload as a proportion of combined workload (calculated using the formula described on page 99).

For bowlers who were uninjured, total bowling workload for the duration of the season was calculated. For bowlers who sustained an injury during the season, only bowling completed prior to the occurrence of injury was calculated, as described in the section regarding statistical procedures in Chapter B1 (page 98). Comparisons of the mean scores between the injured and uninjured bowlers groups were conducted in SPSS (Chicago, Illinois, USA) using independent t-tests and Mann-Whitney U tests for parametric and non-parametric data respectively. For parametric data, the mean score of the continuous risk factor variables for the injured group was compared with the mean of the uninjured group. For non-parametric data, the median score of the continuous risk factor variables was compared [89].

As described in the section regarding statistical procedures in Chapter B1 (page 98), if a bowler sustained multiple injuries or recurrences of an injury within a season, only the workload prior to the first injury occurrence has been reported and when calculating the average weekly workload of individual bowlers, only those weeks in which the player bowled were included.

RRs were calculated using the same formula described on page 102. However, due to the smaller sample size, it was not possible to use the same approach described in Chapter B1, in which the risk factor variables were divided into quintiles, using the middle category as the reference group. In this study, risk of injury was determined by comparing bowlers with a high workload to bowlers with a low workload. Low bowling workload was chosen as the reference group when calculating RRs, so that high bowling workload could be investigated as a risk factor for injury. For reasons of completeness, the risk factor variables were categorised into these high/low groups in two ways: using the values for the 50th percentile (above or below the median) and the values for the 75th percentile (above or below the upper quartile) as the cut-points. Each of the risk factor variables were divided in this way, except for “training workload as a proportion of combined workload”, which was only divided using the value for the 50th percentile. Bowlers with a workload above the cut-point (the 50th or 75th percentile) were classified as having a high workload, whilst bowlers with a workload below the cut-point were classified as having a low workload. As described in the section regarding statistical procedures in Chapter B1 (page 98), these cut-points were rounded to the nearest appropriate number. RRs and confidence intervals were estimated using the Crosstab procedure in SPSS. Those RRs for which the 95% confidence intervals did not include 1.0 were considered significant.

B2.3 Results

Of the 47 bowlers who agreed to participate, 3 bowlers (6.4%) did not provide bowling workload or injury information during the season and were subsequently excluded from the study. Therefore, final analyses were conducted for 44 bowlers of mean age 14.7 (SD = 1.4, range 12 - 17) years.

B2.3.1 Injury occurrence

Eleven of the 44 bowlers (25%) reported a bowling-related repetitive microtrauma injury during the season. Six of these injuries occurred in the first half of the season (October, November, December) and the remaining 5 injuries occurred in the second half of the season (January, February, March). It is beyond the scope of this thesis to investigate the timing of, or the medical details, of these injuries. However to provide an overview, Table 27 lists the frequency of injuries reported in this study according to the OSICS cricket-specific injury categories [129].

Table 27 The frequency of bowling-related injuries reported by adolescent fast bowlers according to the OSICS cricket-specific injury categories

Body region	**OSICS injury category**	**Number of injuries (% of total)**
Upper limb	Shoulder tendon injuries	1 (9%)
Trunk and back	Lumbar stress fractures/reactions	5 (44%)
	Lumbar injuries (other than stress fractures/reactions)	2 (18%)
Lower limb	Quadriceps strain injuries	2 (18%)
	Heel and achilles injuries	1 (9%)

Whilst not meeting the injury inclusion criteria, it is worth noting that 23 of the 44 bowlers (52%) reported back pain at some stage during the season.

B2.3.2 Age at the start of the season as a risk factor for injury

There was no difference in the mean age of the injured and uninjured bowlers (14.8 and 14.7 years respectively, t = 0.157, df = 42, p = 0.876). Accordingly, the risk of injury did not increase for bowlers aged ≥ 15 years (equal to or above the median for the group) as compared with bowlers who were < 15 years of age. The risk of injury was also no different for bowlers aged ≥ 16 years (equal to or above the 75th percentile for the group) as compared with younger bowlers, as shown in Table 28.

Table 28 Age at the start of the season as a risk factor for injury to adolescent fast bowlers

Age at start of the season (years)	**% of injured bowlers in this age group**	**% of uninjured bowlers in this age group**	**RR as compared with bowlers aged less than this**	**95% CI**
≥ 15	36.4	45.5	0.75	0.26, 2.20
≥ 16	18.2	18.2	1.0	0.27, 3.77

B2.3.3 Number of days between bowling occurrences as a risk factor for injury

In comparing the mean number of days between bowling occurrences, injured bowlers had been bowling far more frequently than uninjured bowlers (mean: 3.2 versus 4.6 days between bowling occurrences, respectively). However, the data for the number of days between bowling occurrences did not follow a normal distribution. Therefore, when comparing the injured and uninjured bowlers, the median values were compared using a Mann-Whitney U test. The median number of days between bowling occurrences was significantly lower in injured bowlers compared with uninjured bowlers (median: 3.2 versus 3.9 days respectively, *M* rank: 171.0 and 819.0 respectively, Mann Whitney U = 105.0, p = 0.038). Accordingly, the risk of injury was significantly higher for bowlers with an average of < 3.5 days between bowling occurrences (equal to or above the median for the group), as shown in Table 29.

Table 29 Risk of injury according to the average number of days between bowling occurrences for adolescent fast bowlers

Average number of days between bowling occurrences	% of injured bowlers with this workload	% of uninjured bowlers with this workload	RR as compared with bowlers with a greater number of days between bowling occurrences	95% CI
< 3.5	63.6	27.3	3.06	1.06, 8.87
< 3.0	27.3	21.2	1.28	0.41, 3.92

* Significant RRs are shaded

The association between workload and injury was also investigated for training and match occurrences separately. In comparing the mean number of days between training bowling occurrences, injured bowlers had been bowling significantly more frequently than uninjured bowlers (mean: 4.8 and 8.1 days respectively, t = -2.141, df = 41, p = 0.038). The risk of injury was significantly higher for bowlers with an average of < 6.0 days between training bowling occurrences (equal to or above the median for the group). There was also a trend towards an increased risk of injury for bowlers with an average of < 4.0 days between training bowling occurrences (equal to or above the 75^{th} percentile for the group), as presented in Table 30.

Table 30 Risk of injury according to the average number of days between training bowling occurrences for adolescent fast bowlers

Average number of days between bowling occurrences	% of injured bowlers with this workload	% of uninjured bowlers with this workload	RR as compared with bowlers with a greater number of days between bowling occurrences	95% CI
< 6.0	70.0	30.3	3.57	1.07, 11.9
< 4.0	40.0	15.2	2.52	0.90, 7.05

* Significant RRs are shaded

When considering match workload only, injured bowlers had also been bowling more frequently than uninjured bowlers, with significantly fewer days between match bowling occurrences (mean: 7.5 and 12.0 days respectively, t = -2.450, df = 42, p = 0.019). The risk of injury was higher for bowlers with an average of < 9.0 days between match bowling occurrences (equal to or above the median for the group) as compared with bowlers with an average of ≥ 9.0 days between match bowling occurrences, with the RR approaching significance. Bowlers with an average of < 7.0 days between match bowling occurrences (equal to or above the 75th percentile for the group), were at a significantly increased risk of injury. These results are presented in Table 31.

Table 31 Risk of injury according to the average number of days between match bowling occurrences for adolescent fast bowlers

Average number of days between bowling occurrences	% of injured bowlers with this workload	% of uninjured bowlers with this workload	RR as compared with bowlers with a greater number of days between bowling occurrences	95% CI
< 9.0	72.7	36.4	3.20	0.98, 10.49
< 7.0	45.5	9.1	3.80	1.51, 9.28

* Significant RRs are shaded

When considering training workload as a proportion of combined workload, there was no difference in the mean proportions of the injured and uninjured bowlers (mean: 0.38 and 0.40 respectively, t = -0.315, df = 41, p = 0.775). There was also no association with the risk of injury, as shown in Table 32.

Table 32 Risk of injury for adolescent fast bowlers according to training workload as a proportion of combined workload, with respect to the number of days between bowling occurrences

Training workload as a proportion of combined workload	% of injured bowlers with this proportion	% of uninjured bowlers with this proportion	RR	95% CI
< 0.40	70.0	51.5	Ref	
≥ 0.40	30.0	48.5	0.54	0.16, 1.82

B2.3.4 Number of bowling days per week as a risk factor for injury

There was no difference between injured and uninjured bowlers with respect to the mean number of bowling days per week (mean: 2.6 versus 2.3 sessions respectively), but not significantly so (t = 1.079, df = 42, p = 0.287).

There was a trend towards an increase in the risk of injury for bowlers with an average of ≥ 2.5 bowling days per week (equal to or above the median for the group) as compared with bowlers with an average of < 2.5 days, as shown in Table 33.

Table 33 Risk of injury according to the average number of bowling days per week for adolescent fast bowlers

Average number of bowling days per week	% of injured bowlers with this workload	% of uninjured bowlers with this workload	RR as compared with bowlers with a lesser number of bowling days per week	95% CI
≥ 2.5	63.6	33.3	2.53	0.87, 7.38
≥ 3.0	18.2	12.1	1.41	0.40, 5.00

When investigating training workload only, there was no difference between injured and uninjured bowlers when considering the number of training bowling days per week (mean: 1.99 and 1.65 days respectively, t = 1.732, df = 41, p = 0.091). There was a trend towards an increased risk of injury for bowlers with an average of ≥ 2.0 bowling days per week (equal to or above the 75th percentile for the group), as shown in Table 34.

Table 34 Risk of injury according to the average number of training bowling days per week for adolescent fast bowlers

Average number of bowling days per week	% of injured bowlers with this workload	% of uninjured bowlers with this workload	RR as compared with bowlers with a lesser number of bowling days per week	95% CI
≥ 1.5	80.0	63.6	1.93	0.47, 7.93
≥ 2.0	50.0	21.2	2.58	0.91, 7.35

Similarly, there was no difference between injured and uninjured bowlers with respect to the mean number of match bowling days per week (mean: 1.29 and 1.23 days respectively, t = 0.765, df = 42, p = 0.449). There was a trend towards an increase in the risk of injury for bowlers with an average of ≥ 1.5 match bowling days per week (equal to or above the 75th percentile for the group), as presented in Table 35.

Table 35 Risk of injury according to the average number of match bowling days per week for adolescent fast bowlers

Average number of bowling days per week	% of injured bowlers with this workload	% of uninjured bowlers with this workload	RR as compared with bowlers with a lesser number of bowling days per week	95% CI
≥ 1.2	63.6	63.6	1.00	0.35, 2.90
≥ 1.5	27.3	9.1	2.38	0.87, 6.52

When considering training workload as a proportion of combined workload, there was no difference in the mean proportion of the injured and uninjured bowlers (mean: 0.59 and 0.56 respectively, t = 1.275, df = 41, p = 0.209). As shown in Table 36, there was a trend towards an increased risk of injury for bowlers with a proportion of ≥ 0.55 (equal to or above the median for the group) as compared with bowlers with a proportion of < 0.55. However, this was not significant.

Table 36 Risk of injury for adolescent fast bowlers according to training workload as a proportion of combined workload, with respect to the number of bowling days per week

Training workload as a proportion of combined workload	% of injured bowlers with this proportion	% of uninjured bowlers with this proportion	RR	95% CI
< 0.55	10.0	42.4	Ref	
≥ 0.55	90.0	57.6	4.82	0.67, 34.52

B2.3.5 Number of deliveries per bowling day as a risk factor for injury

There was no difference between injured and uninjured bowlers for the average number of deliveries per bowling day (mean: 46.7 versus 44.1 deliveries respectively, $t = 0.858$, $df = 42$, $p = 0.396$). When investigating the risk of injury according to the mean number of deliveries per bowling day, there was a trend towards an increased risk of injury for bowlers with an average of ≥ 50.0 deliveries per day (equal to or above the 75th percentile for the group), as shown in Table 37.

Table 37 Risk of injury according to the average number of deliveries per bowling day for adolescent fast bowlers

Average number of deliveries bowled per day	% of injured bowlers with this workload	% of uninjured bowlers with this workload	RR as compared with bowlers with a lesser number of deliveries per day	95% CI
≥ 45.0	54.5	45.5	1.31	0.47, 3.68
≥ 50.0	45.5	24.2	1.99	0.74, 5.37

When investigating training workload only, the number of deliveries per training bowling day was similar for injured bowlers and uninjured bowlers (mean: 36.4 and 37.1 deliveries respectively, $t = -0.226$, $df = 41$, $p = 0.822$). Accordingly, there was no association between deliveries per training bowling day and risk of injury, as shown in Table 38.

Table 38 Risk of injury according to the average number of deliveries per training bowling day for adolescent fast bowlers

Average number of deliveries per day	% of injured bowlers with this workload	% of uninjured bowlers with this workload	RR as compared with bowlers with a lesser number of deliveries per day	95% CI
≥ 35.0	60.0	60.6	0.98	0.32, 2.97
≥ 45.0	20.0	18.2	1.09	0.28, 4.20

There was no difference between injured and uninjured bowlers for the mean number of deliveries per match bowling day (mean: 51.7 and 53.9 deliveries respectively, t = -0.579, df = 42, p = 0.565). There was no association between the number of deliveries per match bowling day and injury, as presented in Table 39.

Table 39 Risk of injury according to the average number of deliveries per match bowling day for adolescent fast bowlers

Average number of deliveries per day	% of injured bowlers with this workload	% of uninjured bowlers with this workload	RR as compared with bowlers with a lesser number of deliveries per day	95% CI
≥ 55.0	36.4	54.5	0.57	0.19, 1.68
≥ 60.0	18.2	33.3	0.53	0.13, 2.12

When considering training workload as a proportion of combined workload, there was no difference in the mean proportion between injured and uninjured bowlers (mean: 0.42 and 0.41 respectively, t = 0.421, df = 41, p = 0.676). As shown in Table 40, there was a trend towards an increased risk of injury for bowlers with a proportion of ≥ 0.40 (equal to or above the median for the group), as compared with bowlers with a proportion of < 0.40.

Table 40 Risk of injury for adolescent fast bowlers according to training workload as a proportion of combined workload, with respect to the number of deliveries per bowling day

Training workload as a proportion of combined workload	% of injured bowlers with this proportion	% of uninjured bowlers with this proportion	RR	95% CI
< 0.40	20.0	48.5	Ref	
≥ 0.40	80.0	51.5	2.88	0.69, 11.99

B2.3.6 Number of deliveries bowled per week as a risk factor for injury

As with the average number of deliveries bowled per session, there was not a significant difference between injured and uninjured bowlers for the average number of deliveries bowled per week (mean: 113.9 versus 101.9 deliveries respectively, $t = 0.923$, $df = 42$, $p = 0.361$). Accordingly, there was no association between the number of deliveries per week and risk of injury, as shown in Table 41.

Table 41 Risk of injury according to the average number of deliveries bowled per week for adolescent fast bowlers

Average number of deliveries bowled per week	% of injured bowlers with this workload	% of uninjured bowlers with this workload	RR as compared with bowlers with a lesser number of deliveries per week	95% CI
≥ 100.0	45.5	39.4	1.20	0.43, 3.35
≥ 130.0	27.3	24.2	1.13	0.36, 3.51

When considering training workload separately, there was no difference in the mean number of training deliveries per week between injured and uninjured bowlers (mean: 74.2 and 62.4 deliveries respectively, $t = 1.051$, $df = 41$, $p =$

0.300). As shown in Table 42, there was no association between the number of deliveries per week and risk of injury.

Table 42 Risk of injury according to the average number of training deliveries bowled per week for adolescent fast bowlers

Average number of deliveries per week	% of injured bowlers with this workload	% of uninjured bowlers with this workload	RR as compared with bowlers with a lesser number of deliveries per week	95% CI
≥ 60.0	60.0	45.5	1.57	0.52, 4.79
≥ 85.0	30.0	24.2	1.25	0.39, 4.00

Accordingly, there was no difference between Injured and uninjured bowlers for the number of match deliveries per week (mean: 74.1 and 66.9 deliveries respectively, t = 1.163, df = 42, p = 0.252). There was a trend towards an increased risk of injury for bowlers with an average of ≥ 70.0 deliveries per match day (equal to or above the median for the group) as compared with bowlers with an average less than this, as shown in Table 43.

Table 43 Risk of injury according to the average number of match deliveries bowled per week for adolescent fast bowlers

Average number of deliveries per day	% of injured bowlers with this workload	% of uninjured bowlers with this workload	RR as compared with bowlers with a lesser number of deliveries per day	95% CI
≥ 70.0	63.6	39.4	2.10	0.72, 6.16
≥ 80.0	27.3	18.2	1.46	0.48, 4.41

Finally, when considering training workload as a proportion of combined workload, the mean proportions were the same for injured and uninjured bowlers (mean: 0.47 and 0.47 respectively, t = 0.099, df = 41, p = 0.922). As shown in Table 44, there was no association between training workload as a proportion of combined workload and the risk of injury.

Table 44 Risk of injury for adolescent fast bowlers according to training workload as a proportion of combined workload, with respect to the number of deliveries bowled per week

Training workload as a proportion of combined workload	% of injured bowlers with this proportion	% of uninjured bowlers with this proportion	RR	95% CI
< 0.45	40.0	45.5	Ref	
≥ 0.45	60.0	54.5	1.19	0.39, 3.61

B2.3.7 Adherence to bowling workload guidelines

Bowling workloads were investigated to determine if the bowlers had been exceeding the Cricket Australia Junior Cricket Policy age-specific workload guidelines (see Table 26). Bowlers had exceeded the guidelines for the number of match deliveries to be bowled per day in only 8% of the match sessions recorded. However, they had exceeded the guidelines for the number of training deliveries to be bowled per day in 42% of the training sessions recorded. The median number of deliveries by which the bowlers exceeded the training bowling guidelines was 12 deliveries, with a large range of 1 to 264 additional deliveries.

B2.3.8 Validity of bowling workload logbooks

A total of 25 training sessions and 25 match sessions were validated during the course of the season. The bowling workload diaries were an accurate method of determining the number of deliveries bowled each day. In 68% of cases, there was exact agreement with the number of deliveries reported by the bowler and the number of deliveries reported by the research assistant and in 94% of cases the maximum difference was 2 deliveries.

B2.4 Summary of results

Listed below are the significant findings identified in this study:

Combined workload (match + training)

- The median number of days between bowling occurrences was significantly lower in injured bowlers compared with uninjured bowlers (median: 3.2 versus 3.9 days respectively).

- Risk of injury was significantly increased for bowlers with the least (< 3.5) number of days between bowling occurrences, as compared with bowlers with an average of ≥ 3.5 days between bowling occurrences.

Match workload only

- Injured bowlers had been bowling significantly more frequently than uninjured bowlers (mean: 7.5 and 12.0 days respectively).

- Risk of injury was significantly increased for bowlers who had bowled the most frequently (< 7.0 days between match bowling occurrences), as compared with bowlers with an average of ≥ 7.0 days between match bowling occurrences.

Training workload only

- Injured bowlers had been bowling significantly more frequently than uninjured bowlers (mean: 4.8 and 8.1 days respectively).

- Risk of injury was significantly increased for bowlers who had bowled the most frequently (< 6.0 days between training bowling occurrences), as compared with bowlers with an average of ≥ 6.0 days between training bowling occurrences.

B3: Bowling workload, technique and physical characteristics as risk factors for repetitive microtrauma injury to adolescent and adult fast bowlers

This chapter describes the results obtained from a risk factor study conducted with adolescent and adult fast bowlers during the 2003-04 season. This study was developed using information provided by the workload studies described in Chapters B1 and B2. These workload studies demonstrated that bowling workload was significantly associated with an increased risk of injury to fast bowlers, but it was acknowledged that to develop a solid evidence base for broader fast bowling injury prevention strategies that it was also necessary to investigate a range of potential risk factors. This chapter provides information regarding the association between a range of potential risk factors and repetitive microtrauma injury to adolescent and adult fast bowlers.

B3.1 Introduction

The previous two chapters (B1 and B2) have demonstrated that bowling workload is significantly associated with injury to both adult and adolescent fast bowlers. However, bowling workload is only one of three factors believed to predispose a fast bowler to injury. Previous research has reported that overuse (in terms of bowling volume), poor technique and poor physical preparation [61, 105, 147] may all combine to increase the risk of injury to fast bowlers. As described in section A2.11 in the Literature Review, whilst a significant body of research investigating the role of bowling technique in the occurrence of back injury has contributed to the development of guidelines for fast bowlers and their coaches, there is limited literature that has investigated the association between the physical characteristics of fast bowlers and injury. Furthermore, very few studies have investigated a range of proposed injury risk factors concurrently, with most research focusing on one facet only.

The susceptibility of fast bowlers to injury was acknowledged by Cricket Australia in the early 1990's. In response, they developed an injury prevention initiative referred to as the "SPOT" program (<u>S</u>creening, <u>P</u>hysical Preparation, <u>O</u>verbowling, <u>T</u>echnique) [147], as part of the NPBP. The SPOT program described guidelines for bowling workload, technique and physical preparation, for bowlers aged under 19 years. As part of this SPOT program, the NPBP asked each state cricket association to conduct basic technique, fitness and musculoskeletal screenings with fast bowlers (aged 12 years and over) selected in the high performance squads to identify injury risk factors.

The main objective of this prospective cohort study was to concurrently investigate measures of bowling workload, bowling technique and physical characteristics as risk factors for repetitive microtrauma injury to adolescents and adult fast bowlers, with the intention of developing evidence-based injury prevention guidelines. For the prospective cohort study to produce valid results, it is essential that the tools used to measure the potential injury risk factors are reliable. Therefore, a reliability assessment of the tools used for the baseline screening was conducted, to inform the development of appropriate field-based screening protocols for fast bowlers. The results of this reliability assessment are presented in Part C of this thesis.

As described in the Introduction and Literature Review, this project had an epidemiological focus. Whilst incorporating biomechanical and medical perspectives, the study was not intended to provide detailed biomechanical analyses or to investigate the medical issues surrounding the injuries sustained. It is acknowledged that the screening protocols used were not necessarily “gold standard” laboratory based tests, but the study was designed to identify reliable field-based screening protocols that could be easily used in the cricket “real world” by cricket coaches, physiotherapists and fitness trainers.

B3.2 Methods

B3.2.1 Bowler recruitment

The state cricket associations for New South Wales and Queensland were approached to participate in this study and both agreed. Players were eligible to participate if they had been selected in the male Under 13 years, Under 15 years, Under 17 years, Under 19 years, Under 23 years or state high performance squads for season 2003-04. The coaches for each of these squads in both states were asked to identify 7 - 8 players within each squad (of a total of approximately 25 – 30 cricket players), that were fast bowlers. Each state association was also asked to recruit 7 – 8 bowlers, of any age, participating in grade/club cricket competitions.

Each state cricket association sent an Information Statement (an example of which is attached as Appendix 10) to eligible bowlers and information sessions were held during regular training sessions for bowlers and their parents/guardians (if aged under 18 years). A total of 109 high performance bowlers were identified and 86 agreed to take part, giving a response rate of 79%. Of the remaining 23 bowlers, 7 were ineligible to participate due to injury (as bowlers who were injured at the time of baseline testing were not eligible to be recruited into the study), 5 were unable to attend any of the scheduled baseline testing sessions, and 11 refused to participate due to a lack of interest in the study. A total of 16 grade/club bowlers were also identified as being eligible to participate but only 5 agreed to take part, giving a response rate of 31%. Of the remaining 11 bowlers, 4 were unable to attend any of the scheduled baseline testing sessions, and 7 refused to participate due to a lack of interest in the study. All participating bowlers (and a parent/guardian for those aged under 18 years) completed a consent form prior to undertaking baseline testing. The project was approved by the University of New South Wales Human Research Ethics Committee (Appendix 11).

B3.2.2 Baseline screening protocols and testing procedures

Participants in the study underwent a series of physical tests at the commencement of the 2003-04 season. This baseline screening consisted of three major components: a musculoskeletal assessment, a fitness and anthropometric assessment and a two dimensional multiple plane analysis of bowling technique. As part of the NPBP, state associations have conducted a basic musculoskeletal assessment of the fast and fast-medium bowlers in their high performance squads since the mid 1990’s. Hence, the tests chosen for inclusion in the assessments conducted in this research project were based on those in the current NPBP protocols.

As described previously, the model of injury causation developed by Bahr and Krosshaug was adopted in the program of research described in this thesis [148]. Therefore, after reviewing the relevant scientific literature pertaining to fast bowling injuries, as well as considering the current NPBP protocols, a number of potential risk factors were identified for further investigation in this study. These included intrinsic risk factors such as the bowling technique used, measures of physical fitness and body composition. Bowling workload (load) was considered as a mechanism of injury.

As described in the literature [29] and the previous two chapters of this thesis, the majority of injuries reported among fast bowlers are to the back, trunk and lower limb. This therefore establishes their priority for prevention. The identification of injury risk factors for these particular body regions was the primary focus when selecting tests for inclusion in the baseline screening protocol.

Research assistants employed in each state contacted the participating bowlers to book appointments for them to attend the scheduled testing sessions. Where possible, bowlers completed all three components of the baseline screening during one appointment. However, due to availability of testing staff and equipment, several bowlers were asked to attend two appointments on different days to complete the baseline screening.

Musculoskeletal assessment

As part of the NPBP, state associations have conducted a basic musculoskeletal assessment of the fast and fast-medium bowlers in their high performance squads since the mid 1990's. The protocol they use is primarily a subjective assessment of posture, flexibility and stability and is conducted by a sports physiotherapist. For the purposes of this research project, this existing protocol was adapted with the assistance of a Cricket Australia sports physiotherapist, to develop a more objective assessment of flexibility, strength and stability. The tests chosen were based on clinical assessment protocols widely used with athletes [89] and incorporated procedures described in the relevant literature [149, 150]. Whilst some tests have been evaluated for their reliability [146], the reliability of several of the tests chosen had not previously been established. Therefore, a reliability assessment of the protocol used in this study was conducted; the results of this are outlined in Chapter C2.

Bowlers were tested whilst lying on a standard physiotherapy bench, unless otherwise specified. They were asked to wear training shorts only. They were given thorough instructions prior to performing any of the tests and were told why the measurement was being performed. For range of motion tests, the tester (a sports physiotherapist) first stabilised the proximal bony segment of the joint being measured, to ensure the intended motion was isolated [89]. Once the bowler was positioned for the range of motion test and stabilised, the tester moved the joint passively through the available range of motion. This was done so that the bowler was made aware of the movement being tested and the tester could make an assessment of the bowler's available range of motion and then confirm this with the goniometric measurement [143]. For those tests requiring goniometric measurement, a modified goniometer was used. A spirit level was attached to one arm of the goniometer, so that the degree of motion relative to the vertical could be determined. Where tests were undertaken for both sides of the body, the measurements were recorded for the “bowling” and “non-bowling” sides of the body, rather than the “left” and “right” sides of the body. Therefore, for a right-handed bowler, tests on the right side of the body were classified as the “bowling” side and tests on the left side of the body were classified as the “non-bowling” side. Accordingly, for a left-handed bowler, tests on the left side of the body were classified as the “bowling” side and tests on the right side of the body were classified as the “non-bowling” side. This was done so that differences between the dominant and non-dominant sides of the body could be identified in the baseline screening tests.

The tests chosen for the musculoskeletal assessment and the procedures used are described below, in the order in which the tests were conducted. As stated previously, the majority of the tests were chosen to identify possible risk factors for back, trunk and lower limb injuries. The screening protocol that was issued to the testers is attached as Appendix 12. Throughout this section, the physiotherapist is referred to as the “tester”, and the research assistant who assisted the physiotherapist with the testing is referred to as the “assistant”.

1. Knee extension

Hamstring muscle tightness has been historically thought of as a possible cause of hamstring injury [42]. The knee extension test was used to assess hamstring muscle length and the range of assisted active knee extension in a position of hip flexion [109]. The procedure used for this test was adapted slightly from the process described by Harvey (1998). The bowler was instructed to lie in a supine position, with their hip of the testing leg flexed at 90° and their arms crossed on their chest. The tester provided support behind the posterior thigh to hold the hip in 90° flexion, whilst the bowler was instructed to relax their foot and slowly straighten their knee. Once the bowler had reached their limit of extension, the tester provided support behind the calf, whilst an assistant to the tester recorded knee extension (x°), relative to the vertical, to the nearest degree. The final angle was then calculated as 90° - x°.

In cases where the bowler was able to achieve full knee extension in this position, the tester flexed the knee and moved the thigh to 30° past the vertical position. With a relaxed foot, the knee was again straightened until the bowler had reached their limit of extension and the assistant recorded knee extension (x°), relative to the vertical, to the nearest degree. The final angle was then calculated as 120° - x°.

2. Modified Thomas Test (hip extension)

Tightness of the hip flexors has been proposed to cause increased anterior pelvic tilt and lumbar lordosis during running. The result of this will be impingement of the vertebral facet joints of the lumbar spine, which is proposed to be a causative factor in the development of low back pain [40]. The purpose of the Modified Thomas Test (MTT) is to assess the flexibility of the hip flexors. The procedure used was the same as that described in previous research [105]. The bowler was asked to perch on the end of the bench and roll back into a supine position, whilst holding both knees firmly to their chest. The bowler held their contralateral hip in maximal flexion with both arms, whilst their testing leg was lowered towards the floor. An assistant supported this position by pushing gently on the contralateral knee. The bowler was asked to relax the hip and thigh muscles of their testing leg so that a passive end point position was obtained due to gravity alone. The axis of the goniometer was placed over the greater trochanter, with the fixed axis directed vertically using the spirit level. The moveable arm of the goniometer was pointed toward the lateral knee joint line, representing the line of the femur. The tester then assessed the hip angle relative to the horizontal, or 0° axis, as a positive or negative angle, to the nearest degree. ie. -7° represented a hip flexed above the horizontal and 12° represented a hip that was extended below the horizontal.

3. Modified Thomas Test (hip abduction)

As well as measuring hip flexion, the MTT can also be used to measure the degree of hip abduction. The procedure used was adapted slightly from that used in previous research [67]. The bowler was asked to perch on the end of the bench and roll back into a supine position, whilst holding both knees firmly to their chest. The bowler held the contralateral hip in maximal flexion with both arms, whilst their testing leg was lowered towards the floor. An assistant held the contralateral hip in maximal flexion and the bowler crossed their arms on their chest. The assistant added external rotation to the contralateral hip in order to move the anterior superior iliac spine (ASIS) of the left and right side into a parallel alignment. Hip abduction angle was measured with the centre of the goniometer over the ipsilateral ASIS, with the flexible arm positioned to the opposite ASIS. Hip abduction was recorded as a positive or negative angle, to the nearest degree, with the line perpendicular to that of the ASIS considered as 0°. ie. -7° represented hip adduction and 12° represented hip abduction.

4. Hip internal and external rotation

It has been proposed that the range of hip internal rotation and external rotation is an aetiological factor in the occurrence of lower limb and lumbar spine injury in athletes [29, 77, 151]. This test was used to assess the range of hip rotation in a neutral hip position [152]. Range of hip rotation was measured in prone with the hip extended and the knee flexed, because in this position none of the musculature which limits hip internal rotation is taut. If hip internal rotation was measured at 90º of hip flexion then the gluteus maximus could be pulled taut and this could limit the range of hip internal rotation [78]. The bowler lay in a prone position with both knees bent to 90°, chin resting on the bench, arms by their sides. To determine internal rotation, the bowler was asked to let both of their ankles move away from each other as far as possible, whilst the tester ensured that pelvic motion and/or hip flexion did not occur. To determine external rotation, the bowler straightened their contralateral knee and let the ankle of their testing leg drop towards the opposite side of the body as far as possible. For both internal and external rotation, the assistant measured the angle formed by the line of the tibia, relative to the vertical, as determined by the spirit level goniometer [151]. The angle was recorded to the nearest degree.

5. Combined elevation test

The purpose of the combined elevation test is to assess combined thoracic extension (strength and range of motion), shoulder girdle flexion and scapula retraction [153]. The bowler lay in a prone position on the floor, with both of their arms outstretched in front of them. They were instructed to keep their elbows extended, thumbs locked together and palms facing towards the floor. For the duration of the test, the bowler kept their feet, hips, chest and chin on the ground. They were asked to take a breath in and hold, and then raise both of their arms off the floor as high as possible, without flexing their elbows. A tape measure was used to measure the perpendicular distance from the base of the metacarpal of the thumb to the floor, to the nearest 0.5cm.

6. Prone four point hold

This test was chosen to assess lower abdominal strength and endurance. Trunk muscle fatigue has been highlighted to be of importance in the development of low back pain [77]. The bowler lay in a prone position on a towel on the floor, resting on their forearms, with their elbows flexed at 90°. Their forearms were held parallel to each other, shoulder width apart. Bowlers were not permitted to grip their hands together at any stage during the test. Their feet were placed in a push-up position, with their ankles flexed and the base of their toes on the floor. Bowlers were instructed to pull their navel in towards their spine and hold. They then raised their trunk off the floor, resting on their forearms and toes, holding a neutral lumbopelvic position as long as possible. The test was terminated if the bowler experienced back pain, if they could no longer hold the neutral position (as determined by the tester) or if they could simply not sustain the prone hold any longer. A stopwatch was used to determine the length of time the bowler held a neutral position, to the nearest second.

7. Bridging hold

The purpose of the bridging hold is to assess gluteal strength and endurance. The gluteus maximus muscle has been shown to contribute to sacroiliac joint force closure which appears to be an important mechanism in effective and safe load transference from the lower limbs to the lumbar spine [154]. Assessing strength and endurance of this muscle would be particularly important in fast bowling due to the repetitive nature of fast bowling and the high ground reaction forces on back and front foot landing which may be a causative factor in injury. The bowler lay supine on the floor, with both knees bent at 90°. They raised their hips and pelvis off the floor in order to attain a continuous alignment from the shoulder, through the hip, through to the knee. They then raised their contralateral foot off the floor and with their foot in a neutral position, fully extended their knee. The bowler was asked to use the gluteal muscles to keep their hips up and stop the lower back from arching. They held this position for as long as possible, until the position was no longer held correctly (as determined by the tester), the bowler experienced low back or hamstring pain or could simply not hold the position any longer. A stopwatch was used to determine the length of time the bowler held the position, to the nearest second. This was completed once for each leg.

8. Ankle dorsiflexion lunge

The purpose of this test is to measure the range of dorsiflexion at the ankle joint and mobility in the midfoot. It has been suggested that restricted ankle dorsiflexion plays a vital biomechanical role in foot and ankle problems [76]. As described by Harvey [76], a tape measure was fixed along the floor with the 0cm point at the junction of the floor and wall. The bowler positioned their foot on the tape on the floor so that their heel line and big toe were aligned on the tape measure. The tester held the bowler's heel to prevent it from lifting off the floor and manually locked the subtalar joint so it remained in a neutral position throughout the test. The bowler lunged forward until their knee touched the wall. The maximum distance from the great toe to the wall was recorded to the nearest 0.1cm.

9. Calf heel raises

This test was used to assess endurance of the ankle plantarflexor muscles in a weightbearing task. Compromised function of the calf muscle may increase load on the knee and patellar tendon via the closed kinetic chain [155]. Improved calf muscle strength may help reduce the risk of lower limb stress fracture [156]. With bare feet, the bowler stood with the balls of their feet on the edge of a step with their heels off the step. The bowler was instructed to stand on one foot and to rise onto the ball of that foot as high as possible, then slowly lower their heel, whilst maintaining knee extension throughout the movement. The heel raise/lower cycle was repeated continuously (without a rest) until the bowler was unable to raise through full range with the knee extended. They were asked to perform the heel raises at a rate of approximately one cycle per second.

Two dimensional multiple plane analysis of bowling technique

One of the major components of the NPBP is the continuing assessment of bowling technique. Since the mid 1990's, as part of the NPBP, coaches have subjectively assessed fast bowling technique by watching video footage of the bowling action and using a checklist to identify problem areas. In the early 2000's, this system was updated to incorporate the use of the siliconCOACH video motion analysis software (Sport and Physical Education Technology Ltd). In collaboration with the Cricket Australia Sports Science Officer (Marc Portus), a siliconCOACH representative developed a number of analysis templates for use in cricket. One of these templates was designed for use with fast bowlers and incorporated various biomechanical and technical measurements of the fast bowling action, based on risk factors identified in previous research. As part of the NPBP, digital video cameras and laptop computers, along with the siliconCOACH software, were distributed by Cricket Australia to the majority of the state cricket associations in 2002. Therefore, this system was available to be used in this study.

For the purposes of this research, the template for use with fast bowlers was adapted slightly to include additional technical measurements of bowling technique. A detailed procedures manual was also developed by the author of this thesis, in collaboration with the Cricket Australia Sports Science Officer (Marc Portus), and distributed to the two participating state associations (Appendix 13). Whilst it has been used in a number of different sports and activities, the inter-rater and intra-rater reliability of siliconCOACH motion analysis software had not been previously evaluated for its use in cricket. Therefore, a reliability assessment was conducted and the results are described in Chapter C3.

The tests chosen for the two dimensional multiple plane analysis of bowling technique and the procedures used are described below.

1. Camera preparation

The technique analysis required video footage of the bowling action to be recorded by side-on and overhead digital cameras. These cameras were set from the bowling crease at the distances outlined below in parts a) and b). The cameras were fully zoomed in, so as to reduce the depth of field of the image and therefore reduce perspective error [157].

In most cases, lighting was adequate to film at the rate of 25 frames per second, which the siliconCOACH software was then able to analyse at 50Hz. Where possible, filming was conducted outdoors in the early afternoon to ensure as much natural daylight as possible. When using indoor facilities, lights were set as bright as possible to ensure the shutter speed of the camera would operate as fast as possible. It was not possible to manually alter the shutter speed of the cameras used.

a) Side-on camera set up

Where possible, the camera was set up 10m away from the bowling crease, perpendicular to the bowling direction (and plane of motion) and on the bowling side of the body (eg. for a right-handed bowler, the camera was on the right side of the bowler as they were bowling). The camera was set up perpendicular to the line joining the middle to middle stump. It was mounted on a tripod, set level and kept still, as panning shots would have interfered with calculating the measures of speed. The camera was focussed halfway between the popping crease and the bowling crease, with the background as plain and uncluttered as possible. The height of the camera was approximately equal to the height of the bowler's centre of mass (approximately just below the navel). This was to ensure that measurements of height and length were not distorted by the camera angle. Figure 10 shows the set up for the side-on camera.

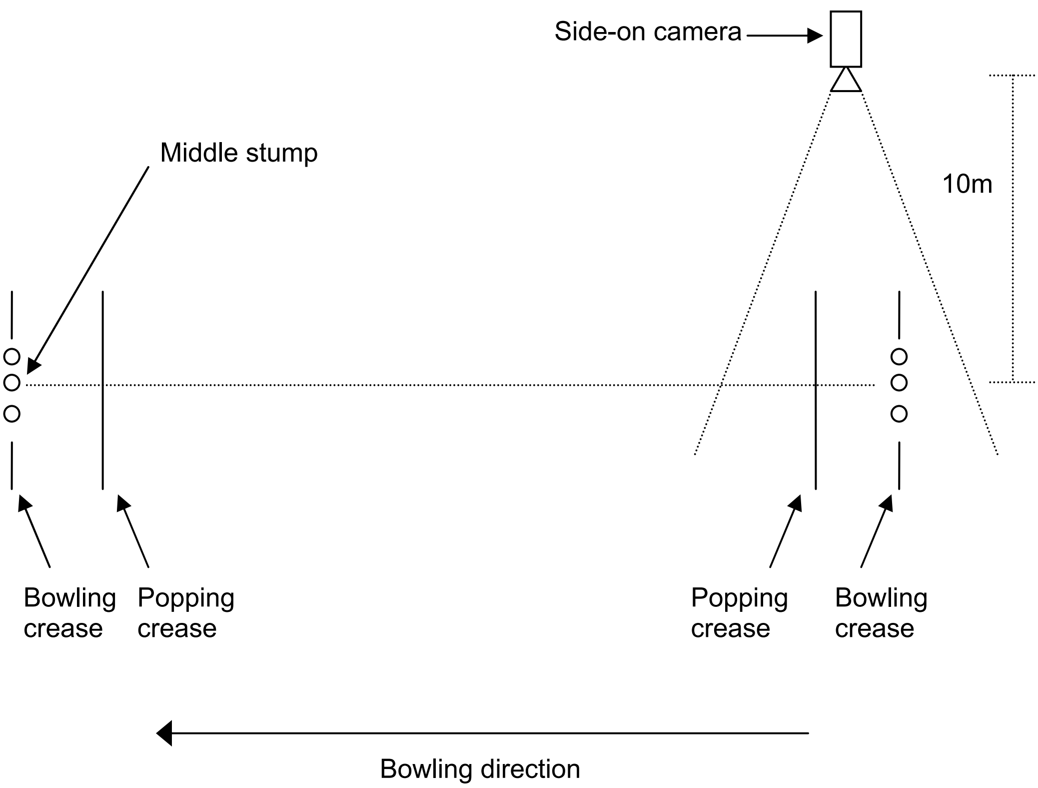


Figure 10 Side-on camera set up for analysis of bowling technique

b) Overhead camera set up

The facilities at each of the state cricket associations largely determined the height that the overhead camera was mounted. In NSW, all filming was conducted indoors. The camera was fixed to the top of the indoor nets, which were 4.00m off the ground. In Queensland, filming was conducted outdoors, using a specialised tripod to hold the camera 3.35m off the ground.

The overhead camera was placed directly above the bowling crease and focussed halfway between the popping crease and the bowling crease. The camera was mounted perpendicular to the floor and kept still.

2. Bowler preparation

To ensure that the measurements calculated in siliconCOACH were as accurate as possible, bowlers were instructed to wear bike pants or tights only, along with their usual training shoes. The following sites (as shown in Figure 11) were marked using tape and/or a non-permanent black marker to allow digitisation in siliconCOACH:

- A - acromion processes (shoulder)
- B - medial and lateral humeral epicondyle (elbow)
- C - ulnar and radial styloid (wrist)
- D - greater trochanter (side of hip)
- E - anterior superior iliac spine (ASIS - front of hip)
- F - medial and lateral femoral epicondyle (knee)
- G - medial and lateral malleolus (ankle)

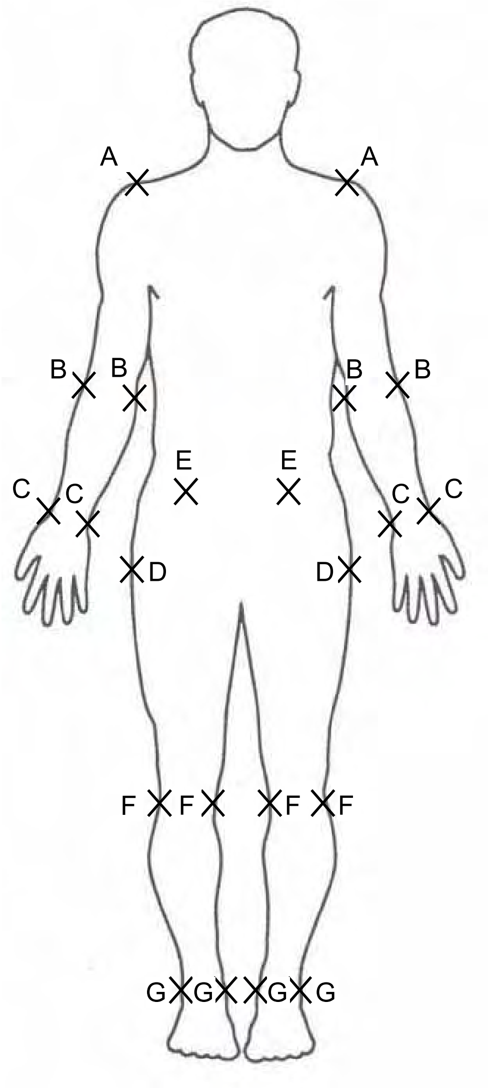


Figure 11 Sites of body markers for analysis of bowling technique

3. Video capture

The bowlers were instructed to warm up and be ready to bowl at full match pace. They were asked to bowl a minimum of four legal deliveries (front foot no-ball law) over the wicket whilst being filmed. For the purposes of standardised analysis, the bowler was instructed to attempt to bowl a good line and length.

4. Analysis of video footage using the siliconCOACH software

For the analysis of video footage, it is preferable that a single delivery is analysed from both the side-on and overhead views, as opposed to analysing separate deliveries for each view. However, to allow a single delivery to be used for both side-on and overhead views, a mixer or dual capture facility is required. At the time of baseline testing, not all of the state associations had access to this expensive equipment. Queensland Cricket had this equipment and it was used in this study. However, Cricket NSW did not and therefore, manual synchronisation was conducted for the footage of the bowlers from NSW. This involved synchronising a delivery filmed with the overhead camera, with a different delivery filmed with the side-on camera, using ball release as the synchronisation point.

The following protocol was used when analysing the side-on and overhead video footage in siliconCOACH to determine measurements for various parameters of bowling technique. This protocol was developed with the assistance of the Cricket Australia Sports Science Officer (Marc Portus) and my co-supervisor, Professor Bruce Elliott, a biomechanist who is considered a leading expert in fast bowling research.

a) Setting the scale for measurements

When using the measurement tools in siliconCOACH to determine distance and speed in the analysis of the footage recorded by the side-on camera, the distance between the bowling and popping creases (1.22m) was used to set the measurement scale.

b) Determining back foot impact and front foot impact

Back foot impact (BFI) and front foot impact (FFI) were determined by the point in time when the foot was in first full contact with the ground. If the heel did not contact the ground during the back foot landing, BFI was defined as the frame that the movement of the foot about the toe had completed. If the movement of the foot about the toe continued throughout the back foot landing, BFI was defined as the frame when the foot was most stable and was bearing the greatest load, prior to the bowler pushing off the toe of the back foot. As BFI and FFI are used several times throughout the analysis, the time of the frame chosen for these impacts was recorded using the stopwatch function in siliconCOACH.

When determining the frame of BFI and FFI in the footage recorded by the overhead camera, synchronised footage from the side-on camera was used to allow the feet to be seen more clearly.

c) Stride length

Stride length was determined using footage recorded by the side-on camera, measured from the back of the heel of the back foot at BFI to the back of the heel of the front foot at FFI, to the nearest centimetre.

A normalised stride length was also calculated using the standing height of the bowler, as measured in the fitness and anthropometric assessment. Stride length was expressed as a percentage of the standing height of the bowler, recorded to the nearest percent.

d) Front knee angle

Footage recorded by the side-on camera was used to calculate the angle of the front knee at FFI, using the line formed by the medial malleolus marker, medial femoral epicondyle marker and up the middle of the thigh. This angle was also recorded when the front knee was most flexed after FFI and prior to, or at, the frame of ball release. The angle of the front knee at FFI and the maximum angle of the front knee between FFI and ball release were recorded to the nearest degree.

e) Height of ball release

The distance from the ground directly under the front foot to the centre of the ball was measured in the frame of ball release, using footage recorded by the side-on camera. The height was recorded to the nearest centimetre.

A normalised height of ball release was also calculated using the standing height of the bowler, as measured in the fitness and anthropometric testing. The height of ball release was expressed as a percentage of the standing height, to the nearest percent.

f) Ball speed

Using footage recorded by the side-on camera, ball speed was calculated from the frame at ball release (the first frame the ball is not in contact with the hand) to one frame after ball release, to the nearest km/h.

g) Shoulder angle at BFI

Using footage recorded by the overhead camera, and the acromion process body markers as a guide, a line was drawn through the primary alignment of the shoulders at the frame of BFI. This line was continued down the pitch, parallel to the alignment of the pitch. The angle of the shoulders, relative to the pitch alignment in the direction of bowling, was then recorded to the nearest degree.

h) Minimum shoulder angle

Using footage recorded by the overhead camera, the frame in which the shoulders obtained the most side-on position between BFI and ball release (usually just before FFI) was identified. As with shoulder angle at BFI, the angle of the shoulders, relative to the pitch alignment in the direction of bowling, was recorded to the nearest degree.

i) Shoulder counter-rotation

This parameter was automatically determined by subtracting the minimum shoulder angle from the shoulder angle at BFI. This measured how much the bowler rotated their shoulders to a more side-on position after BFI, to the nearest degree.

Fitness and anthropometric assessment

As with the musculoskeletal assessment, state associations have conducted basic fitness and anthropometric assessment of the fast bowlers in their high performance squads since the mid 1990's as part of the NPBP. The tests included in this protocol were chosen for their ease of use in the field environment and because they required very little specialised testing equipment. For the purposes of this research, this existing protocol was adapted slightly after reviewing the relevant literature [77, 158], consulting with Cricket Australia coaching (Richard Done), sports science (Marc Portus) and medical staff (Patrick Farhart) and sports science staff at the Queensland Academy of Sport (Peter Herzig, Shaun D'Auria), all of whom had considerable experience in testing cricketers.

The tests centred primarily on body composition, strength, power and aerobic fitness, as recommended by a physiology expert (Dr David Pyne) at the AIS. The reliability of several of the tests chosen had not previously been established, therefore, a reliability assessment of the protocol used in this study was conducted and these results are presented in Chapter C4.

Unfortunately, the equipment used to conduct the vertical jump and 40m sprint tests differed between the two states. Due to the cost of purchasing the "vertec" vertical jump device and electronic timing gates required to conduct these tests, arrangements were made to hire the equipment in each state. The baseline screening was completed in Queensland using this specialised equipment as planned. However, on the day of commencement of testing in NSW, notification was received that the equipment was no longer available to use. Due to this late notification, it was not possible to make arrangements to hire the equipment from another agency. Therefore, alternative testing procedures were used, as described below in points 4 and 8.

Bowlers were asked to wear their normal training clothes and comfortable running shoes. Prior to testing, they completed a warm up consisting of a short run and stretching. The tests chosen for the fitness and anthropometric assessment and the procedures used are described below, in the order in which the tests were conducted. The screening protocol that was issued to the testers is attached as Appendix 14.

1. Height

A tape measure was fixed to a vertical wall. The barefooted bowler stood erect with their heels together and arms hanging naturally by their sides [159]. The heels, buttocks, upper part of the back and back of the head were in contact with the wall, with their weight evenly distributed on both feet. The bowler was instructed to look straight ahead and take a deep breath [160]. A set square was then placed at the most superior aspect of the head, in contact with the tape on the wall. The bowler then stepped away from the wall and the height of the bowler was recorded to the nearest 0.1cm.

2. Body mass

The body mass of bowlers was assessed using electronic digital scales [161], as it was not possible to use the recommended beam-type balance in both testing locations [77]. The scales were placed on a hard, level surface and bowlers were assessed while wearing shorts only. Bowlers were instructed to stand on the scales without support, with weight evenly distributed on both feet. Mass was measured to the nearest 0.1kg.

3. Skinfolds

Prior to skinfold assessment, the landmarks listed below were identified and marked, as outlined by Norton and colleagues [162]. Landmarks are identifiable skeletal points found by palpation that generally lie close to the body's surface and are the "markers" for identifying the exact location of the measurement site:

- Acromiale – the point at the most lateral, superior border of the acromion process and which is midway between the anterior and posterior borders of the deltoid muscle when viewed from the side.

- Radiale – The point at the most superior lateral border of the head of the radius.

- Mid-acromiale-radiale – The point equidistant from acromiale and radiale. This point is projected to the posterior and anterior surfaces of the arm as a horizontal line.

- Subscapulare – The undermost tip of the inferior angle of the scapula.

- Iliospinale – The most inferior aspect of the anterior superior iliac spine.

Once the landmarks were identified, skinfolds were assessed using Harpenden calipers, with all measurements taken on the right side of the body and recorded to the nearest 0.1mm, as recommended by Norton and colleagues [163].

a) Triceps

This skinfold was raised on the marked posterior mid-acromiale-radiale line. The fold was parallel to the line of the upper arm.

b) Biceps

This skinfold was raised on the marked anterior mid-acromiale-radiale line. The fold was parallel to the line of the upper arm.

c) Subscapular

This skinfold was raised at the marked site 2cm along a line running laterally and obliquely downward from the subscapulare landmark at an approximate 45° angle as determined by the natural fold lines of the skin.

d) Supraspinale

This fold was raised at the point where the line from the iliospinale landmark to the anterior axillary border intersects at the horizontal level of the superior border of the ilium. The fold ran medially downward at about a 45° angle.

e) Abdominal

This was a vertical fold raised 5cm from the right side of the omphalion (midpoint of the navel).

f) Front thigh

The bowler's knee was bent at 90° by placing their foot on a box. The site was marked parallel to the long axis of the femur at the midpoint of the distance between the inguinal fold and the superior border of the patella.

g) Medial calf

The bowler was asked to stand with their foot on a box, with their knee bent at 90° and calf relaxed. A vertical fold was raised on the medial aspect of the calf at a level where it has maximal circumference.

As recommended by the International Society for the Advancement of Kinanthropometry, the measurements for these sites were added together to determine the sum of seven skinfolds [164].

4. Vertical jump

The equipment used to measure the vertical jump height differed between the two states, with a yardstick jumping device used in Queensland and a wall-mounted board used in NSW. Previous research has compared the two methods and concluded that the yardstick method (mean = 60cm) produces a 3cm greater mean jump height than the board method (mean = 57cm) [165]. Statistical analyses therefore adjusted for the state squad from which the bowlers were recruited (NSW or Queensland), as described in the data management and statistical procedures section on page 182.

Testing in Queensland - The bowler stood straight, wearing training shoes, with feet flat on the floor and extended their bowling arm and fingers fully to reach as high as possible on a yardstick vertical jump device (vertec). The vertec device consists of a stand with a number of movable vanes that indicate the jump height. The bowlers knocked the plastic vertec fingers and the number of the vertec fingers left in place was recorded as their starting height. The bowler then performed a countermovement jump by bending down at the knees before immediately driving upwards using both arms [166]. They were not permitted to complete any preliminary steps or shuffling. As they performed the countermovement jump, they stretched out their bowling hand and knocked the plastic vertec fingers. The highest jump from 3 trials, with a rest period of 10 – 15 seconds between trials, was recorded. The starting height was subtracted from the peak height to determine the height jumped in centimetres.

Testing in NSW – The test in NSW was conducted using a wall-mounted vertical jump board. The bowler dipped their fingers in chalk, stood straight, wearing training shoes, with their feet flat on the floor. They then extended the bowling arm and fingers fully to leave a chalk mark on the wall at the height of full stretch. The height of the initial mark was recorded. The bowler then performed a countermovement jump by bending down at the knees before immediately driving upwards using both arms. They were not permitted to complete any preliminary steps or shuffling. As they performed the countermovement jump, they stretched out the bowling hand and left a chalk mark on the wall. The highest jump from 3 trials, with a rest period of 10 – 15 seconds between trials, was recorded. The starting height was subtracted from the peak height to determine the height jumped in centimetres.

5. Overhead medicine ball throw

The overhead medicine ball throw was conducted in a similar fashion to a soccer throw in. The bowler stood on a grass surface, wearing training shoes with their feet shoulder width apart. They held a 3kg medicine ball directly above their head with elbows bent slightly. They then took one step forward, whilst lowering the medicine ball back behind their head. They then extended the elbows, brought the ball over their head and threw the ball out in front of them as far as possible. They were advised to release the ball at an angle of approximately 35°. Both feet stayed grounded at ball release. After they had released the ball, the front foot stayed planted, but they were allowed to take one step forward with their back foot to meet the front foot as a follow through. A countermovement swing prior to the throw (ie. attempting to gain momentum by bringing the ball down in front of the chest prior to drawing it back over the head) was not permitted. A tape measure was placed along the ground with the front edge of the bowler’s front foot on 0cm. The distance for each throw was measured to the middle of the ball bounce. The best of three attempts, to the nearest 5cm, was recorded.

6. Chest medicine ball throw

The bowler sat on a grass surface with their back against a wall, legs extended in front of them, knees straight, with hips bent at 90°. They held a 3kg medicine ball with both hands against their chest, with elbows bent. They then extended their elbows and pushed the ball directly out in front of them as far as possible using both hands. They were advised to throw the ball at an angle of approximately 45°, starting from their chest, not from the stomach upwards. A countermovement swing was not permitted (ie. extending elbows in front of them, then drawing the ball into the chest before throwing). They were also not permitted to throw the ball using one hand. A tape measure was placed along the ground starting at the base of the wall. The distance to the middle of the ball bounce was measured. The distance for the best of three attempts, to the nearest 5cm, was recorded.

7. Side-on medicine ball throw

The bowler stood with their feet shoulder width apart, feet facing perpendicular to the direction of the throw. For a right-handed bowler, the left foot was the leading foot. For a left-handed bowler, the right foot was the leading foot. The bowler held the ball in both hands directly in front of their body at hip height, with arms outstretched. They then bent the knees slightly and swung the ball backwards, keeping the arms straight. They then swung the ball back in front of them and released to the side as far as possible (the movement was similar to a golf swing). Their arms remained outstretched throughout the throw and both feet remained grounded throughout the throw. They were advised to throw the ball at an angle of approximately 45°. On ball release, the bowler was permitted to pivot the back foot medially about the toe, but not to lift it off the ground. A tape measure was placed along the ground, with the front edge of the bowler’s leading foot on 0cm. The distance from the start of the tape to the middle of the ball bounce was measured. The distance for the best of three attempts, to the nearest 5cm, was recorded.

8. 40 metre sprint

The equipment used to record the time of the 40m sprint differed between the two states, with electronic timing light gates used in Queensland and hand-held stopwatches used in NSW. Statistical analyses therefore adjusted for the state squad from which the bowlers were recruited (NSW or Queensland), as described in the data management and statistical procedures section on page 182.

Testing in Queensland – This test was conducted on a dry, short mown grass surface, with bowlers wearing their spiked cricket shoes. The running lane was set up so that the bowlers were running perpendicular to the direction of any wind. Electronic timing light gates were placed at the start line and at 40m. Reflectors were placed directly opposite timing gates at a distance of 2m. The bowler stood with the toe of their preferred front foot up to the start line. The bowler was instructed to hold the start position (ie. no rocking back and forth) before the start. The tester then gave the instructions “ready, set, go”, with the bowler starting to run on “go”. The bowler was told to run as fast as possible and not to stop until they had run past the last timing gate at 40m. Electronic timing light gates recorded the start time and the finish time at 40m. The bowler completed two trials approximately 5 minutes apart, with the times recorded for both attempts to the nearest 1/100 of a second.

Testing in NSW – This test was conducted on a dry, short mown grass surface, with bowlers wearing their spiked cricket shoes. The running lane was set up so that the bowlers were running perpendicular to the direction of any wind. Witches hats were set up 5m apart for the length of the 40m sprint. The lane was set at a width of 2m. The bowler stood with the toe of their preferred front foot up to the start line. The bowler was instructed to hold the start position (ie. no rocking back and forth) before the start. The tester then gave the instructions “ready, set, go”, with the bowler starting to run on “go”. The bowler was told to run as fast as possible and not to stop until they had run past the last timing gate at 40m. The tester, using a hand-held stopwatch, recorded the time the bowler passed through the 40m mark. The bowler completed two trials approximately 5 minutes apart, with the times recorded for both attempts to the nearest 1/100 of a second.

9. Yo-yo intermittent recovery test

This test was used in place of the traditionally used multistage fitness test (commonly known as the “beep test” or “shuttle run”) as described in the literature [167]. The use of the yo-yo intermittent recovery test with soccer players has previously been described [168] and the procedures for administering the test, as described below, have been published [169].

Two markers were positioned exactly 20m apart from each other. A third marker was also positioned 5m behind and slightly to the side of the start marker. An audio cassette, provided with the testing material, was used to give instructions to those completing the test as well as to emit signals to control the timing of the test. After listening to the instructions on the audio tape, the bowler ran forward 20m at the time of the first signal. The bowler was instructed to adjust the running speed so that they reach the 20m marker exactly at the time of the next signal. A turn was made at the 20m marker and the bowler ran back to the first marker. After the start marker was passed the bowler continued forward at a lower tempo, ran around the cone 5m away and returned to the start marker, where they waited for the next signal. The time allowed for this jog around the 5m marker was 10 seconds.

As the test progressed, the time at which the bowler needed to run the 20m shuttle progressively increased as controlled by the audio tape (ie. the time between the signals was shortened). With all participants, Level 1 of the Intermittent Recovery Test was used, which consisted of four running bouts at 10 – 13km/h (0 – 160m), seven running bouts at 13.5 – 14 km/h (160 – 440m), whereafter it continued with stepwise 0.5km/h increments after every eight running bouts [170].

The course was repeated until the bowler was unable to maintain the indicated speed for two trials. The first time the marker was not reached a warning was given and the next time, the bowler was instructed to stop. A recording sheet was used to indicate the speed level at which the bowler withdrew from the test, as well as the total number of metres completed.

B3.2.3 Assessing bowling workload

As with the studies presented in B1 (page 93) and B2 (page 126) of this thesis, bowling workload was assessed in this study by examining the frequency of bowling (measured in days) and the type of bowling performed (match or training).

The methods of bowling workload data collection used in this study were the same as those described in B2 on page 126. All participants were asked to complete daily bowling logbooks (attached as Appendix 15) and record the number of training, match and warm-up deliveries bowled each day throughout the 2003-04 season. This diary was then forwarded via email or post to the research assistant in the bowler's home state and entered into a central

Microsoft ACCESS database. Bowling completed in organised one or two-day matches was categorised as match workload. Training workload included formal training sessions or personal training.

B3.2.4 Injury surveillance

The definition of injury used in this study was the same as described in Chapter B2 on page 128. As described in Chapter B1, injury surveillance with first-class players only included major matches, defined as Test matches and one-day international matches involving the Australian squad and all domestic first-class matches (Pura Cup) and domestic one-day matches (ING Cup) involving the six state squads. For the adolescent players participating in this study, a match was defined as any organised fixture during the season, including club, school and representative games.

Bowlers were asked to report any condition or injury, even if it was unrelated to cricket, in their logbooks. A list of the injury concerns reported by the bowlers was prepared by the research assistant in each state on a fortnightly basis throughout the season. This list was then given to a sports physiotherapist, who contacted each bowler to determine the date, cause, site, nature and mechanism of injury as well as to determine if the injury met the inclusion criteria. Injury diagnosis was coded in a cricket-specific modification of the OSICS system [170]. The mechanism of injury field included options such as a collision with another player, being hit by the ball, pushing off to run, gradual bowling, gradual running, slipping or tripping.

Injuries included in the analysis were repetitive microtrauma injuries as a result of gradual bowling. Therefore, all injuries had an insidious onset caused by repetitive episodes of microtrauma. Accordingly, collision-type injuries, such as colliding with another player, were excluded. Unless they met any of the listed criteria, injuries that occurred during training or only affected participation in training sessions were not included in the analysis. All participating bowlers were contacted again at the end of the season to ensure that no injury data were missing.

B3.2.5 Encouragement strategies

It became apparent within the first six weeks of the study that many of the participating bowlers were not submitting bowling workload logbooks to the research assistants on a regular basis. Therefore, to encourage the participants in the study to contribute regular bowling workload data, a high-profile Australian Test and one-day international fast bowler, Brett Lee, was approached to be an ambassador for the project. A letter drafted and signed by Brett was sent to all 91 participants in the study, describing his injury experiences and strategies for reducing injury risk. The letter also encouraged the bowlers to complete the workload diaries for this project. Each letter was personally signed by Brett and sent to the participants in November 2003. A copy of the letter is attached as Appendix 16.

All participating bowlers were also contacted regularly by the research assistant employed in their state, by email or telephone. Bowlers who contributed bowling workload and injury information were contacted by the research assistant and receipt of this information was acknowledged. The research assistants also contacted bowlers who had not returned the workload and injury data as requested, encouraging them to submit this information. Bowlers who had still not responded within a fortnight were contacted by the author of this thesis, to discuss any difficulties they had in completing or returning the bowling logbook and to develop strategies for their continuing contribution to the study.

B3.2.6 Data management and statistical procedures

The results of the baseline screening, in addition to workload and injury data collected during the season, were entered into a central Microsoft ACCESS database and then imported into SPSS (Chicago, Illinois, USA).

The main outcome measure of interest in this study was repetitive microtrauma injury (for the purpose of brevity hereafter referred to as 'injury', unless otherwise specified). Injury was coded as a yes/no variable in SPSS. As described in the section regarding statistical procedures in Chapter B1 (page 98), if a bowler sustained multiple injuries or recurrences of an injury within a season, only the first injury occurrence has been reported. Two additional variables were created to record the diagnosis and body region of each injury, as determined by the cricket-specific version of OSICS[167]. Injuries were assigned to one of four broad body regions: head and neck, upper limb, trunk and back, and lower limb.

To provide an overview of the bowlers participating in this study, descriptive statistics (mean, standard deviation, median and range) were calculated in SPSS for each of the baseline screening variables. The continuous baseline screening variables were also categorised into approximate tertiles for comparison with the outcome of injury. The categories were defined as “low”, “medium” and “high”. This categorisation was done to improve the practical interpretation of the results, as described in the statistical procedures section in Chapter B1. For each of the variables, the chosen reference group was the group with the highest measurement for that variable. No assumption was made as to whether the “low”, “medium” or “high” groups were the preferred, or “best” performing category.

Although standardised protocols were used in both NSW and Queensland for the baseline screening, to ensure that the state squad was not modifying the relationship between the baseline screening variables and injury, a comparison between the results obtained in each state was conducted. The mean scores of each of the baseline screening variables were compared using independent t-tests and Mann-Whitney U tests for parametric and non-parametric data respectively [170].

To assess the relationship between the risk factor variables and injury, logistic regression analyses were conducted using a standard process of statistical model building [167]. Unadjusted logistic regression analyses were first conducted to identify univariate associations between each of the risk factor variables and the outcome of injury. For each of the variables, odds ratios (ORs) were calculated relative to the reference category (denoted as ‘Ref’), which was the group with the highest measurement for that variable. For each OR, 95% CIs were calculated and a p-value for each variable was determined. The ORs were adjusted for the state squad from which the bowlers were recruited (1 = New South Wales, 2 = Queensland). Those variables with a p-value <0.25 in the unadjusted analyses were selected for inclusion in the multivariate model. Chi-square tests were conducted to determine if any of these selected variables were associated with each other to rule out multicolinearity [167].

A multivariate logistic regression analysis was then conducted [167]. A backward stepwise logistic regression procedure based on a likelihood ratio method was used [171]. Due to the small sample size, the probability for stepwise inclusion and exclusion criteria were set at 0.10 and 0.15 respectively. Odds ratios and their associated 95% confidence intervals were calculated, again adjusting for state squad and all other variables. As per a standard statistical process, associations with a p-value <0.10 were considered significant and selected for inclusion in the final model [168].

Finally, those variables that were identified as having a significant association with injury in the backward stepwise logistic regression analysis were included in a logistic regression model using an Enter method, to determine the final model parameters and OR effects [168]. Odds ratios and their associated 95% confidence intervals were calculated, adjusting for state squad and all other variables in the final model. Associations with a p-value <0.10 were considered significant. The goodness-of-fit of the final model was determined using the Hosmer-Lemeshow test.

To describe the relationship between workload and injury, the intention was to compare the bowling workload of injured and uninjured bowlers, using the procedures described in Chapter B1. However, despite regular encouragement and the successful use of logbooks in the study described in Chapter B2, only 43 of the 91 bowlers (47.3%) provided any bowling workload information during the course of the season in this study. Of these 43 bowlers, many only provided information for a limited number of sessions at the start of the season and did not provide complete data for the entire season (mean and median = 31 sessions, SD = 27.9, range = 1 – 164 sessions). It was not possible to retrieve this bowling workload information from other sources for all participating bowlers. Whilst match scorecards were readily available for bowlers participating in state level or grade competitions, it was not possible to obtain scorecards for the remaining competitions, such as junior club cricket. It was also not possible to obtain training bowling workload information for any of the participating bowlers from other sources. Therefore, due to this lack of data, bowling workload was not included in the final analyses. This is a major limitation of this study and prevented the conduct of multivariate analyses of workload, technique and physical characteristics as risk factors for repetitive microtrauma injury to adolescent and adult fast bowlers. This was exceptionally disappointing in light of the associations found between workload and injury in the studies described in Chapters B1 and B2. However, detailed information regarding bowling technique and physical characteristics were collected for the 91 bowlers in this study and analyses were conducted to investigate the association between these factors and injury.

B3.3 Results

B3.3.1 Description of the participating bowlers

Of the 91 bowlers participating in the study, 43 (47.3%) were recruited from Queensland and 48 (52.7%) were recruited from NSW. Seventy-two (79.1%) were right-handed bowlers and 19 (20.9%) were left-handed bowlers. The mean age of bowlers was 18.7 years (SD = 4.56, median = 17.8 years), with a range of 12.3 – 33.1 years (note: data missing for 1 case). As per the age criteria for the NPBP recommendations [172], 53 bowlers (58.2%) were considered adolescent bowlers (aged ≤ 18 years) and 38 (41.8%) were considered adult bowlers (>18 years).

Musculoskeletal assessment

As shown in Table 45, there was little difference between the mean values for the bowling and non-bowling sides of the body in the musculoskeletal assessment. However for many of the variables measured, a wide range of values were recorded. This may be due to the recruitment of both adolescent and adult fast bowlers in this study, the reliability of the tests (the reliability analysis is presented in Part C) or variability between state squads (as shown in Table 49 and discussed in section B3.3.3).

Table 45 Musculoskeletal assessment of adult and adolescent fast bowlers (n = 91)

Baseline test	Bowling side			Non-bowling side		
	Mean (SD)	Median	Range	Mean (SD)	Median	Range
Knee extension (°)	68 (16.2)	67	33 – 120	68 (16.1)	67	36 – 120
Modified Thomas Test (hip extension) (°)[1]	-3 (7.0)	-4	-17 – 15	-3 (7.3)	-3	-18 – 12
Modified Thomas Test (hip abduction) (°)[1]	10 (4.4)	10	2 – 25	11 (5.4)	11	-2 – 28
Hip internal rotation (°)	35 (9.3)	35	15 – 58	34 (9.8)	35	10 – 55
Hip external rotation (°)	41 (10.2)	41	21 – 75	44 (9.9)	43	24 – 76
Ankle dorsiflexion lunge (cm)[2]	12.9 (2.99)	13.0	5.0 – 19.5	12.6 (3.13)	13.0	5.5 – 21.0
Calf heel raises[2]	20 (7.0)	20	6 – 44	20 (6.0)	19	6 – 32
Bridging hold (sec)[3]	50 (40.2)	42	2 – 207	48 (42.4)	40	3 – 296
Prone four point hold (sec)[2]	99 (52.8)	93	11 – 240	- - - - - - - - - - Not applicable - - - - - - - - - -		
Combined elevation test (cm)[4]	17.8 (8.16)	17.5	2.5 – 42.0	- - - - - - - - - - Not applicable - - - - - - - - - -		

Data missing for: [1] 2 cases; [2] 1 case; [3] 3 cases; [4] 4 cases

Analysis of bowling technique

As with the musculoskeletal assessment, there was a wide range of scores recorded for many of the bowling technique variables, as shown in Table 46. This may be due to the bowlers in this study using different bowling techniques and therefore adopting a range of body positions at BFI, FFI and ball release.

Table 46 Two dimensional multiple plane analysis of the bowling technique of adult and adolescent fast bowlers (n = 92)

Baseline test	Mean (SD)	Median	Range
Stride length (m) [1]	1.41 (0.195)	1.40	0.96 – 1.92
Normalised stride length (%) [2]	79 (9.6)	79	53 – 101
Height of ball release (m) [3]	2.15 (0.177)	2.16	1.61 – 2.48
Normalised ball release height (%) [4]	119 (5.6)	119	108 – 133
Front knee angle at FFI (°) [3]	198 (11.5)	197	180 – 225
Maximum front knee angle (°) [3]	210 (16.4)	209	180 – 249
Ball speed (km/h) [5]	110 (13.1)	111	79 – 138
Shoulder counter-rotation (°) [6]	38 (18.2)	38	3 – 81

Data missing for: [1] 6 cases; [2] 9 cases; [3] 7 cases; [4] 10cases; [5] 11cases; [6] 8cases.

Unfortunately, the tests were not able to be conducted with all participating bowlers. This was due to limitations of the video footage that was recorded. For example, ball speed could not be calculated for 11 bowlers as the background in the side-on video footage for those particular bowlers was cluttered and it was simply not possible to see the ball.

Fitness and anthropometric assessment

In accordance with the musculoskeletal assessment and analysis of bowling technique, there were a wide range of scores recorded in the fitness and anthropometric assessment, as presented in Table 47. Again, this may be due to the recruitment of both adolescent and adult fast bowlers in this study.

Table 47 Fitness and anthropometric assessment of adult and adolescent fast bowlers (n = 91)

Baseline test	Mean (SD)	Median	Range
Height (cm) [1]	179.7 (11.02)	181.5	148.5 – 200.0
Body mass (kg) [2]	74.2 (14.94)	77.0	36.7 – 104.3
Sum of seven skinfolds (mm) [3]	72.8 (28.40)	65.4	39.3 – 209.7
Vertical jump (cm) [4]	49 (10.7)	51	22 – 74
Overhead medicine ball throw (m) [5]	9.7 (2.22)	9.9	5.2 – 13.6
Chest medicine ball throw (m) [5]	5.5 (1.23)	5.6	3.0 – 7.5
Side-on medicine ball throw (m) [6]	10.6 (2.90)	10.6	5.3 – 16.9
40m sprint (sec) [7]	5.85 (0.553)	5.75	5.07 – 8.13
Yo-yo test distance (m) [6]	1088 (370.3)	1000	240 – 1960

Data missing for: [1] 4 cases; [2] 12 cases; [3] 23 cases; [4] 28 cases; [5] 21 cases; [6] 22 cases; [7] 26 cases

As noted in Table 47, there were many bowlers for whom the data were missing for the fitness and anthropometric assessment. In cases where it was not possible for a bowler to complete all three components of the baseline screening during the one session, the bowlers completed the musculoskeletal assessment and recorded video footage for the analysis of bowling technique in the first session, and were then asked to return for a second session to complete the fitness and anthropometric assessment. However, many of these bowlers did not attend the second session, or left without completing all of the scheduled tests during the session.

B3.3.2 Injury occurrence

Thirty-seven of the 91 bowlers (40.7%) reported a bowling-related injury during the season. Of the 53 adolescent bowlers participating in the study, 20 (37.7%) were injured. Of the 38 adult bowlers participating in the study, 17 (44.7%) were injured. As described previously, it is beyond the scope of this thesis to investigate the medical details of these injuries. However, a summary of the injuries reported in this study, according to the OSICS cricket-specific injury categories [173] is presented in Table 48.

Table 48 The frequency of bowling-related injuries reported by adult and adolescent fast bowlers according to the OSICS cricket-specific injury categories

Body region	**OSICS injury category**	**Number of injuries (% of total)**		
		Adolescents	**Adults**	**All bowlers**
Upper limb	Shoulder instability	1 (5.0%)	1 (5.9%)	2 (7.4%)
	Other arm and elbow fractures	0 (0.0%)	1 (5.9%)	1 (3.7%)
Trunk and back	Lumbar injuries (other than stress fractures/reactions)	6 (30.0%)	4 (23.5%)	10 (37.0%)
	Side and abdominal strains	3 (15.0%)	0 (0.0%)	3 (11.1%)
	Lumbar stress fractures/reactions	1 (5.0%)	1 (5.9%)	2 (7.4%)
Lower limb	Groin injuries	2 (10.0%)	4 (23.5%)	6 (22.2%)
	Heel and achilles injuries	2 (10.0%)	2 (11.8%)	4 (14.8%)
	Hamstring strain injuries	1 (5.0%)	2 (11.8%)	3 (11.1%)
	Knee tendon injuries	2 (10.0%)	0 (0.0%)	2 (7.4%)
	Shin splints/compartment syndrome	0 (0.0%)	2 (11.8%)	2 (7.4%)
	Foot stress fractures	1 (5.0%)	0 (0.0%)	1 (3.7%)
	Knee cartilage injuries	1 (5.0%)	0 (0.0%)	1 (3.7%)
	TOTAL	20 (100%)	17 (100%)	37 (100%)

The majority of the injuries sustained (91.9%) were back, trunk and lower limb injuries. This is consistent with the findings of previous research [173], as well as with the results presented in Chapter B1 and B2 of this thesis. As the identification of injury risk factors for the back, trunk and lower limb majority was the primary focus when selecting tests for inclusion in the baseline screening protocol, the analysis was restricted to include only the injuries in these particular body regions and exclude the three upper limb injuries.

B3.3.3 Comparison of mean scores between the states

Although standardised protocols were used to conduct the baseline testing, comparisons were made to determine if there were significant differences between the mean results obtained in each state for each of the baseline screening measures. Table 49 lists those variables for which there was a statistically significant difference between the states. *Note:* (B) denotes the ‘bowling’ side of the body and (NB) denotes the ‘non-bowling’ side.

Table 49 Those baseline screening variables with a significant difference between the mean scores for NSW bowlers (n = 43) and Queensland bowlers (n = 48)

Test	Mean for NSW (n = 43)	Mean for Qld (n = 48)	t	df	p-value
Knee extension (B)	74.7	62.8	3.745	89	0.000
Knee extension (NB)	74.1	62.4	3.691	89	0.000
MTT hip extension (B)	1.6	-6.4	6.472	87	0.000
MTT hip extension (NB)	2.2	-7.2	7.985	87	0.000
MTT hip abduction (NB)	12.4	9.8	2.339	87	0.022
Hip internal rotation (B)	38.1	32.1	3.247	89	0.002
Hip internal rotation (NB)	37.2	30.9	3.226	89	0.002
Hip external rotation (B)	45.6	37.4	4.186	89	0.000
Hip external rotation (NB)	48.5	39.3	4.974	89	0.000
Bridging hold (B)	30.3	66.8	Non-parametric analyses conducted		
Bridging hold (NB)	26.9	66.3	-4.886	86	0.000
Calf heel raises (B)	18.5	21.4	-2.011	88	0.047
Combined elevation test	15.0	20.1	-3.037	85	0.003
Yo-yo test distance	1191.2	935.7	2.972	67	0.004

(B) denotes the ‘bowling’ side of the body and (NB) denotes the ‘non-bowling’ side

The data for the bridging hold on the bowling side did not follow a normal distribution and therefore the median values were compared using a Mann-Whitney U test. There was a significant difference between the bowlers in NSW and Queensland (median: 20.0 versus 63.0, *M* rank: 31.1 and 55.6 respectively, Mann Whitney $U = 425.5$, $p < 0.001$).

The differences between NSW and Queensland may be due to differing interpretations of the screening protocols (even though detailed, standardised protocols were developed) or poor reliability of the tests used. The reliability assessment of the protocols is described in Part C.

There was not a statistically significant difference between the states for the baseline screening variables not listed in Table 49.

B3.3.4 Univariate analysis to identify associations between the baseline screening variables and injury

As there was a significant difference between the states for a number of the baseline screening variables, the state squad from which the bowler was recruited (New South Wales or Queensland) was included as a covariate in all analyses. Therefore, all ORs reported have been adjusted for state squad.

The age of bowlers at the time of baseline screening was not associated with sustaining a back, trunk or lower limb injury, as shown in Table 50.

Table 50 Age as a risk factor for trunk, back and lower limb injury to adolescent and adult fast bowlers, adjusted for state squad

Baseline variable	n	% of bowlers in this category who were injured	OR ^	95% CI	p-value
Age (years)					0.641
≤ 17.0	39	41.0	0.93	0.34, 2.53	
17.1 – 20.0	21	28.6	0.58	0.17, 1.95	
> 20.0	30	40.0	Ref		

^ Adjusted for state squad

Musculoskeletal assessment

Table 51 shows the results of the analysis investigating the association of the baseline musculoskeletal tests with back, trunk and lower limb injury. Hip internal rotation (bowling side), ankle dorsiflexion lunge (non-bowling side) and calf heel raises (bowling side) were subsequently selected for inclusion in the multivariate model, with p-values of <0.25 meeting the selection criteria. None of the remaining musculoskeletal tests displayed a significant association with back, trunk and lower limb injury and therefore were not selected for inclusion in the multivariate model.

Table 51 Musculoskeletal assessment measures as risk factors for trunk, back and lower limb injury to adolescent and adult fast bowlers, adjusted for state squad

Baseline test	n	% of bowlers in this category who were injured	OR ^	95% CI	p-value
Knee extension (°) (B)					0.321
≤ 60	27	44.4	1.93	0.63, 5.88	
61 – 70	29	31.0	0.81	0.28, 2.37	
> 70	35	37.1	Ref		
Knee extension (°) (NB)					0.884
≤ 60	30	36.7	1.32	0.44, 4.00	
61 – 70	27	37.0	1.15	0.39, 3.41	
> 70	34	38.2	Ref		
MTT hip extension (°) (B)					0.291
≤ -7	31	22.6	0.49	0.13, 1.84	
-6 – 0	28	46.4	1.24	0.40, 3.82	
> 0	30	46.7	Ref		
MTT hip extension (°) (NB)					0.550
≤ -7	31	25.8	0.77	0.19, 3.17	
-6 – 0	31	45.2	1.41	0.44, 4.50	
> 0	27	44.4	Ref		
MTT hip abduction (°) (B)					0.699
≤ 8	33	42.4	1.50	0.48, 4.72	
9 – 12	34	35.3	1.02	0.32, 3.20	
> 12	22	36.4	Ref		
MTT hip abduction (°) (NB)					0.734
≤ 8	29	41.4	1.54	0.49, 4.78	
8 – 12	30	33.3	1.12	0.35, 3.54	
> 12	30	40.0	Ref		
Hip internal rotation (°) (B)					0.233
≤ 30	29	27.6	0.40	0.12, 1.32	
31 – 40	38	34.2	0.45	0.16, 1.30	
> 40	24	54.2	Ref		
Hip internal rotation (°) (NB)					0.336
≤ 30	30	23.3	0.46	0.13, 1.61	
31 – 40	39	43.6	1.00	0.34, 2.90	
> 40	22	45.5	Ref		

Table 51 (continued from previous page)

Baseline test	n	% of bowlers in this category who were injured	OR ^	95% CI	p-value
Hip external rotation (°) (B)					0.752
≤ 35	24	33.3	0.78	0.23, 2.59	
36 – 45	37	32.4	0.67	0.24, 1.90	
> 45	30	46.7	Ref		
Hip external rotation (°) (NB)					0.814
≤ 35	16	31.3	1.25	0.30, 5.17	
36 – 45	41	39.0	1.39	0.51, 3.84	
> 45	34	38.2	Ref		
Ankle dorsiflexion lunge (cm) (B)					0.662
≤ 12.0	36	33.3	1.05	0.36, 3.06	
12.1 – 14.0	27	44.4	1.58	0.52, 4.83	
> 14.0	27	33.3	Ref		
Ankle dorsiflexion lunge (cm) (NB)					0.114
≤ 12.0	41	29.3	0.99	0.30, 3.25	
12.1 – 14.0	29	51.7	2.69	0.79, 9.17	
> 14.0	20	30.0	Ref		
Calf heel raises (B)					0.234
≤ 15	22	22.7	0.41	0.10, 1.79	
16 – 25	51	43.1	1.13	0.35, 3.68	
> 25	17	35.3	Ref		
Calf heel raises (NB)					0.412
≤ 15	21	28.6	0.93	0.20, 4.26	
16 – 25	55	41.8	1.79	0.49, 6.55	
> 25	14	28.6	Ref		
Bridging hold (sec) (B)					0.722
≤ 20.0	27	48.1	1.70	0.47, 6.12	
20.1 – 60.0	32	37.5	1.30	0.41, 4.08	
> 60.0	29	27.6	Ref		
Bridging hold (sec) (NB)					0.631
≤ 20	28	42.9	0.60	0.15, 2.36	
21 – 60	30	33.3	0.56	0.17, 1.87	
> 60	30	36.7	Ref		

Table 51 (continued from previous page)

Baseline test	n	% of bowlers in this category who were injured	OR ^	95% CI	p-value
Prone four point hold (sec)					0.304
≤ 60	26	42.3	0.75	0.25, 2.27	
61 – 120	37	27.0	0.44	0.15, 1.27	
> 120	27	48.1	Ref		
Combined elevation test (cm)					0.639
≤ 15.0	36	47.2	1.19	0.42, 3.32	
15.1 – 20.0	18	27.8	0.65	0.18, 2.31	
> 20.0	33	36.4	Ref		

* Variables with p<0.25 selected for the final model are shaded

^ Adjusted for state squad

Analysis of bowling technique

The results of the analysis investigating the association of the bowling technique measures with the outcome of back, trunk and lower limb injury are presented in Table 52. Only one variable, the maximum front knee angle, met the criteria for inclusion in the multivariate model.

Table 52 Bowling technique measures as risk factors for trunk, back and lower limb injury to adolescent and adult fast bowlers, adjusted for state squad

Baseline test	n	% of bowlers in this category who were injured	OR ^	95% CI	p-value
Stride length (m)					0.445
≤ 1.35	33	33.3	1.08	0.36, 3.26	
1.36 – 1.50	25	48.0	1.95	0.62, 6.15	
> 1.50	27	33.3	Ref		
Normalised stride length (%)					0.983
≤ 75	33	36.4	1.12	0.35, 3.61	
76 – 85	28	35.7	1.09	0.32, 3.65	
> 85	21	38.1	Ref		
Height of ball release (m)					0.854
≤ 2.10	33	39.4	1.30	0.47, 3.62	
2.11 – 2.20	16	43.8	1.32	0.37, 4.71	
> 2.20	35	31.4	Ref		
Normalised ball release height (%)					0.960
≤ 115	15	33.3	0.92	0.24, 3.44	
116 – 120	35	37.1	1.10	0.40, 3.05	
> 120	31	35.5	Ref		
Front knee angle at FFI (°)					0.509
≤ 190	27	44.4	1.54	0.52, 4.57	
191 – 200	26	30.8	0.79	0.25, 2.46	
> 200	31	35.5	Ref		
Maximum front knee angle (°)					0.193
≤ 200	28	35.7	1.44	0.43, 4.80	
201 – 220	31	45.2	2.96	0.88, 9.96	
> 220	25	28.0	Ref		
Ball speed (km/h)					0.703
≤ 100	19	36.8	1.20	0.32, 4.46	
101 – 120	39	43.6	1.58	0.52, 4.84	
> 120	22	31.8	Ref		
Shoulder counter-rotation (°)					0.860
≤ 30	30	33.3	0.98	0.31, 3.13	
31 – 50	29	44.8	1.29	0.42, 3.96	
> 50	24	37.5	Ref		

* Variables with p<0.25 selected for the final model are shaded

^ Adjusted for state squad

Fitness and anthropometric assessment

As shown in Table 53, none of the fitness and anthropometric measures were significantly associated with the outcome of back, trunk and lower limb injury and therefore did not meet the criteria for inclusion in the multivariate model.

Table 53 Fitness and anthropometric measures as risk factors for trunk, back and lower limb injury to adolescent and adult fast bowlers adjusted for state squad

Baseline test	n	% of bowlers in this category who were injured	OR ^	95% CI	p-value
Height (cm)					0.869
≤ 175.0	27	40.7	1.24	0.41, 3.71	
175.1 – 185.0	31	32.3	0.93	0.32, 2.76	
> 185.0	29	34.5	Ref		
Body mass (kg)					0.867
≤ 65.0	23	30.4	0.88	0.24, 3.29	
65.1 – 85.0	36	33.3	1.21	0.36, 4.05	
> 85.0	20	35.0	Ref		
Sum of seven skinfolds (mm)					0.799
≤ 55.0	30	36.7	1.41	0.40, 4.93	
55.1 – 80.0	17	23.5	0.95	0.20, 4.39	
> 80.0	21	28.6	Ref		
Vertical jump (cm)					0.802
≤ 45	22	36.4	0.74	0.18, 3.06	
46 – 55	24	33.3	0.62	0.15, 2.56	
> 55	17	35.3	Ref		
Overhead medicine ball throw (m)					0.784
≤ 8.0	20	35.0	0.74	0.22, 2.42	
8.1 – 10.0	17	35.3	0.67	0.19, 2.35	
> 10.0	33	42.4	Ref		
Chest medicine ball throw (m)					0.854
≤ 5.0	27	37.0	1.00	0.32, 3.11	
5.1 – 6.0	15	46.7	1.41	0.38, 5.25	
> 6.0	28	35.7	Ref		

Table 53 (continued from previous page)

Baseline test	n	% of bowlers in this category who were injured	OR ^	95% CI	p-value
Side-on medicine ball throw (m)					0.756
≤ 9.0	21	33.3	0.67	0.18, 2.54	
9.1 – 12.0	28	39.3	1.06	0.31, 3.61	
> 12.0	20	40.0	Ref		
40m sprint (sec)					0.910
≤ 5.50	17	41.2	0.86	0.21, 3.54	
5.51 – 6.00	30	33.3	0.76	0.22, 2.64	
> 6.00	18	38.9	Ref		
Yo-yo test distance (m)					0.362
≤ 800	26	26.9	0.40	0.11, 1.42	
801 – 1300	21	33.3	0.57	0.16, 2.11	
> 1300	22	54.5	Ref		

^ Adjusted for state squad

B3.3.5 Multivariate analysis to identify associations between the baseline screening variables and injury

After following a standard process of statistical modelling [89], four variables met the inclusion criteria for selection in the multivariate model to identify associations between the baseline screening variables and back, trunk and lower limb injury. These were: hip internal rotation (bowling side), ankle dorsiflexion lunge (non-bowling side), calf heel raises (bowling side), and maximum front knee angle. Chi-square analyses confirmed that these variables were not correlated and were therefore eligible for inclusion in the multivariate model as independent predictors. The state squad from which the bowler was recruited was also included as a covariate.

Backwards elimination removed calf heel raises (bowling side) and maximum front knee angle from the model and, as shown in Table 54, two variables were identified as independent predictors of back, trunk and lower limb injury (after adjusting for state squad). Reduced hip internal rotation on the bowling side of the body was associated with a significantly decreased risk of injury and reduced ankle dorsiflexion on the non-bowling side of the body was associated with a significantly increased risk of injury.

The final logistic regression analysis showed that bowlers with hip internal rotation of ≤ 30° on the bowling side of the body were at a significantly reduced risk of injury (OR = 0.20, p = 0.014), as were bowlers with rotation of 30.1° – 40.0° (OR = 0.36, p = 0.076), as compared with bowlers with > 40° of rotation. Additionally, bowlers with an ankle dorsiflexion lunge of 12.1 – 14.0cm on the non-bowling side of the body were at a significantly increased risk of injury (OR = 4.03, p = 0.040), as compared with bowlers with a lunge of > 14cm. Bowlers with a lunge of ≤ 12cm were also at an increased risk of injury, but not significantly so (OR = 1.38, p = 0.611).

Table 54 Independent predictors of trunk, back and lower limb injury to adolescent and adult fast bowlers, adjusted for state squad

Injury predictor	n	OR ^	95% CI	p-value
Hip internal rotation (B) (°)				0.045
≤ 30.0	28	0.20	0.06, 0.73	
30.1 – 40.0	38	0.36	0.12, 1.11	
> 40.0	24	Ref		
Ankle dorsiflexion lunge (NB) (cm)				0.060
≤ 12.0	41	1.38	0.40, 4.84	
12.1 – 14.0	29	4.03	1.07, 15.21	
> 14.0	20	Ref		

^ Adjusted for state squad and for the effects of the other variable

* Significant ORs are shaded

The Hosmer-Lemeshow statistic for goodness-of-fit showed that the data fitted the model well (X^2 = 0.98, df = 7, p = 0.995).

B3.4 Summary of results

Listed below are the significant findings identified in the multivariate analyses in this study:

- Bowlers with hip internal rotation of ≤ 30° on the bowling side of the body were at a significantly reduced risk of injury as compared with bowlers with > 40° of rotation (after adjusting for state squad and ankle dorsiflexion lunge on the non-bowling side of the body).

- Bowlers with an ankle dorsiflexion lunge of 12.1 – 14.0cm on the non-bowling side of the body were at a significantly increased risk of injury as compared with bowlers with a lunge of > 14cm (after adjusting for state squad and hip internal rotation on the bowling side of the body).

PART C RELIABILITY OF SCREENING PROTOCOLS

A limitation of previous risk factor studies reported in the cricket literature is that many have used specialised equipment and facilities to test fast bowlers, and the degree to which the testing procedures can be adopted in the cricket “real world” is unclear. The research described in Chapter B3 of this thesis focused on the investigation of risk factors for repetitive microtrauma injuries to fast bowlers and used field-based screening tests that were adapted slightly from existing protocols used with cricketers and other athletes.

However, it is vital that these field-based screening protocols are reliable (consistent and repeatable) so that the results of these screenings can be used to identify risk factors for injury and subsequently inform the development of injury prevention strategies. It is also important that cricket coaches and medical staff are able to easily, inexpensively and reliably monitor the risk factors for injury to fast bowlers on an ongoing basis. For this reason, reliability assessments of the musculoskeletal, fitness and technique screening protocols used in Chapter B3 of this thesis were conducted.

The importance of the reliability of pre-participation screening protocols and other clinical assessment tools has been identified in a number of published studies [29, 78, 89, 146, 147, 174]. However, a variety of statistical methods to calculate reliability have been reported in these studies, or not stated at all, and it is difficult to determine which method is most appropriate in the context of measuring intrinsic risk factors in sports injury research. A review of the literature was conducted and a particular statistical method developed by Eliasziw and colleagues [175] for the concurrent assessment of inter- and intra-observer reliability was selected. The context within which this method can be used for reliability assessments in sports injury research is described in Chapter C1. The results of the reliability assessment of the screening protocols described earlier in this thesis (Chapter B3) are presented in Chapters C2, C3 and C4.

C1: Determining the inter- and intra-observer reliability of screening tools

This chapter describes a statistical method that was used to determine the reliability of the screening tools described in Chapter B3. This method was developed by Eliasziw and colleagues [176] and it concurrently assesses inter- and intra-observer reliability. A review paper discussing this statistical method and its application to screening tools used in sports injury research has been submitted for publication in a peer-review journal. The paper was developed by the author of this thesis, along with accredited biostatisticians: my supervisor, Professor Caroline Finch and Dr Andrew Hayen. The paper is attached as Appendix 3 (Dennis, R.J., Hayen, A. and Finch, C.F. (2005). Determining the intra- and inter-observer reliability of screening tools used in sports injury research. *Journal of Science and Medicine in Sport,* (submitted – currently under review)).

The author of this thesis contributed information regarding the definition of reliability and its related concepts, described the context within which the statistical method can be applied, and collected the data used in the worked examples. It is this material that is presented in this chapter (C1). Dr Hayen and Professor Finch provided detailed descriptions of the method used, including statistical formulae and calculations. These statistical formulae and calculations will be referred to in this chapter, but the details are only provided in the paper in Appendix 3.

C1.1 Introduction

Over recent years there has been an increasing call to provide a firm evidence base for sports injury prevention initiatives. As argued by Bahr and Krosshaug [177], provision of this evidence base is limited by knowledge about the aetiological factors causing many sports injuries. To redress this imbalance, there needs to be considerably more effort put towards conducting studies to elucidate the intrinsic and extrinsic risk factors for sports injury. As described in the Literature Review, a favoured epidemiological study design to investigate risk factors for sports injuries is the prospective cohort study, which involves collecting data regarding potential injury risk factors before injuries occur [178, 179]. Pre-participation (baseline) screening is a commonly used method for the collection of data relating to potential intrinsic risk factors, measuring factors such as flexibility, muscle strength and athletic technique at baseline [174]. The pre-participation screening is conducted to identify characteristics of the musculoskeletal system that may predispose an athlete to injury, or to identify incomplete recovery from a previous injury [180].

Such screenings involve the measurement of potential risk factors and relating these to injury. In a prospective study, measurements are made on uninjured athletes eg. at the start of a playing season, and these are related to injury outcomes during the following participation period. For intrinsic risk factors, such as strength, flexibility, and balance, it is often of interest to see how these also vary over the playing season or how they differ in injured and uninjured participants at the end of the season. This necessitates taking multiple measurements.

The ability for such studies to clearly identify potential risk factors depends on the accuracy with which these measurements are made [181]. So that the data collected during these pre-participation screenings can be used to identify injury risk factors, and subsequently inform the development of effective injury prevention strategies, it is vital that the screening protocols are reliable [182, 183]. Measurements need to be reproducible over time and by different observers, as well as being repeatable within a given individual. Poor reproducibility limits the ability of researchers to reach conclusions about whether a measured variable is indeed a risk factor for injury, because it is difficult to differentiate participants with or without the variable of interest in the presence of large random measurement error [184].

C1.2 Definition of reliability and its related concepts

Validity of measurement is the degree to which a test measures what it is supposed to measure [171] and reliability refers to the consistency, or repeatability, of a measure [185]. Whilst a measure can be reliable without being valid, the reverse is not true [66, 67]. Low reliability indicates that large variations in measurement will occur upon retesting so that assessment outcomes cannot be meaningfully reproduced or interpreted [81]. Whilst factors such as weight and height are typically measured with high reliability, other potential injury risk factors, such as joint range of motion (ROM), may be more prone to unreliable measurement [76]. Another consequence of unreliability is the need for an increased sample size to detect an important difference between groups for the variable being measured; because of the increased variability in measurement [12]. This has obvious implications for the design of prospective cohort studies and randomised controlled trials that compare controls and intervention groups. In particular, this may result in an unnecessary increase in the cost and timing of conducting such studies.

In clinical assessments, measurement error can be introduced by the human observer (eg. a physiotherapist conducting a clinical assessment) and/or the instrument used (eg. a goniometer). Using the assessment of ROM as an example, if the goniometer itself has been shown to be reliable, then the reliability of the ROM measurements depends on the correct use of the goniometer by the physiotherapist. This chapter deals specifically with the issue of determining the reliability of the human observer, which is the ability of a single observer or multiple observers to produce the same measurements consistently under the same conditions with the same sample [66, 77]. Two forms of observer reliability are discussed:

- intra-observer (or within observer) reliability - the degree to which measurements taken by the same observer are consistent.

- inter-observer (or between observers) reliability - the degree to which measurements taken by different observers are similar.

Related to, but not identical to reliability, is the concept of precision. Precision is defined as the spread in random measurement error that would be expected if repeated independent observations are made on an individual [78]. It is a measure of absolute error, while reliability assesses the effect of that error on the ability to differentiate between individuals [79]. Obviously, if reliability is poor, it will not be possible to have precise measurements.

C1.3 The statistical methods that have been used to determine reliability in published research

The importance of the reliability of pre-participation screening protocols and other clinical assessment tools has been identified in a number of published studies [66, 78, 79, 174, 186-191]. As shown in Table 55, a variety of statistical techniques have been used to establish inter- and intra-observer reliability in these studies. The intra-class correlation coefficient (ICC) is the measure most commonly used for determining the reliability of tests collecting continuous data. Whilst the ICC has been the most often cited reliability measure, a range of models and methods to calculate the ICCs have been used. Many of the intraclass correlation coefficients given in Table 55 are based on a popular set of methods described by Shrout and Fleiss [175]. In many of the ways presented in that paper for calculating an intraclass correlation coefficient, such as the ICC(1,1), ICC(2,1) and ICC(3,1), it assumed that each observer takes only one measurement. This means that these methods cannot be applied to inter-observer reliability studies in which observers make more than one measurement [176]. Researchers also sometimes use the mean value of each observer’s repeated measurements, but this has the effect of inflating the inter-observer reliability as an ICC calculated from the mean of multiple measurements will be higher than that based on a single measurement [177-179]. It is also possible to just use the first of the repeated measurements taken by an observer, but this method is inefficient as it does not use all of the available information. Other studies have been limited because they have not stated the exact method they used to calculate the ICC.

Table 55 Overview of the methods used to determine inter-observer and/or intra-observer reliability in published research

Authors		Data collection	Inter-observer	Intra-observer	How calculated
Gabbe et al [174]	Lower extremity musculoskeletal screening tests	2 raters, 15 subjects, 2 sessions, 2 trials per rater per session	ICC (2,1)	ICC (3,1)	Used mean of two trials per rater
Scott et al [180]	Comparison of two dynamometers assessing hip muscle strength	2 raters, 15 subjects, 2 sessions, 3 trials per rater per session	ICC – calculated from 2 way mixed analysis of variance	ICC – 1 way random effects analysis of variance.	Used mean of three trials, as well as maximal value of the 3 trials
Click Fenter et al [181]	Comparison of three dynamometers measuring hip abduction strength	2 raters, 10 subjects,1 session, 2 trials per rater	ICC (2,1)	ICC (2,1)	Not clear from the presented information
McKenna et al [182]	Clinical examination technique for scapula position	3 raters, 15 subjects, 1 session, 1 trial per rater	ICC (2,1)	n/a	Compare raters using mean scores for 10 subjects across four arms positions
Maulder et al [183]	Comparison of six horizontal and vertical jump tests	6 tests, 10 subjects, 2 sessions, 3 trials per test per session	Inter-class correlation coefficient but no method for calculation is given	n/a	Compare the 6 tests using mean scores for all 10 subjects
Stockbrugger et al [184]	Medicine ball explosive power test	1 test, 20 subjects, 2 sessions, 3 trials per session	ICC (r_1)	n/a	Used best score from each session for comparison

Table 55 (continued from previous page)

Authors		Data collection	Inter-observer	Intra-observer	How calculated
Herrington [171]	Clinical examination technique to determine orientation of the patella	20 raters, 1 subject, 1 session, 3 trials per rater	Inter-class correlation coefficient but no method for calculation is given	n/a	Used mean of 3 trials
Tousignant et al [192]	Use of an inclinometer to measure neck flexion and extension	2 raters, 44 subjects, 2 sessions, 1 trial per rater per session	ICC (2,1)	ICC (1,1)	Used mean of two trials for inter-observer
Peolsson et al [185]	Use of a dynamometer to measure handgrip strength	3 raters, 32 subjects, 1 session, 3 trials per rater	ICCs were calculated using repeated measures one-way ANOVA.	ICCs were calculated using repeated measures one-way ANOVA	Not mentioned
Bennell et al [190]	Weight-bearing lunge measure of ankle dorsiflexion	13 subjects. Inter-observer: 4 raters, 1 session, 3 trials per rater. Intra-observer: 2 raters, 2 sessions, 3 trials per rater per session	ICC (2,3)	ICC (3,3)	Mean of 3 trials used
Clark et al [187]	Adapted crossover hop for distance	1 observer, 12 subjects, 2 sessions, 3 trials per session	NA	ICC (2,1)	Maximum hop distance was used

C1.4 Selecting an appropriate statistical method to determine inter- and intra-observer reliability

Because a variety of statistical methods to calculate reliability have been reported in the literature, or not stated at all, it is difficult to determine which method is most appropriate in the context of measuring intrinsic risk factors in sports injury research. After considering the approaches available, a statistical method developed by Eliasziw and colleagues [185] was selected for use in this thesis. A particular advantage of the Eliasziw et al. method over the methods used in previous studies, is that it uses each individual measurement to concurrently determine inter- and intra-observer reliability.

With respect to the reliability assessments conducted in this thesis (described in Chapters C2, C3 and C4), a short time interval separated the testing sessions and it must be noted that the reliability of the measurements represents their reproducibility only within this particular time frame. Test-retest assessments within a short time interval tend to demonstrate higher reliability than those studies with longer time intervals, which may be influenced by a number of uncontrolled variables [78]. Although, reliability studies with short time intervals may be appropriate for those studies collecting pre-participation data, longer periods of time between assessments (eg. 1 week or 1 month) are important for clinical assessments where there is a need to evaluate patient improvements over time [175].

When conducting a reliability study, there are two main situations to consider:

1. the observers are assumed to have been drawn randomly from a larger population (random observers)

2. the observers are the only ones of interest (fixed observers).

This is an important distinction because the formulas for calculating the reliability differ slightly for these two scenarios. The reliability assessments conducted in this thesis have used the random observers approach, because the results had to be generalisable to a larger population of people conducting the musculoskeletal screening, analysis of bowling technique and fitness testing. Conversely, in the clinical setting, for example, two clinicians monitoring the progress of a patient may be the only people that will ever assess this patient. Hence, the results of a reliability assessment would not need to be applied to any other raters and the observers are fixed.

Eliasziw and colleagues have recommended that appropriate statistical tests, CIs and the standard error of measurement (SEM) should be calculated along with the reliability coefficients [176]. The CIs summarise the uncertainty (precision) in an estimated reliability coefficient by providing a range of values that is likely to contain the true population value [177]. The SEM, also known as measurement error, allows the observer to establish whether any changes in measurements are a result of real clinical change or irrelevant fluctuations [178]. The SEM is expressed in the same units as the test was measured (eg. degrees, centimetres, seconds) and is comparable in interpretation to a standard deviation. The inter-observer SEM is particularly important within the context of the research described in this thesis, as different observers recorded measurements that were used to determine the risk of injury in Chapter B3. The formula for determining the inter-observer SEM reflects not only the disagreement among observers but also the imprecision with which the individual observers make their measurements [179]. It is possible to translate the test statistic for the SEM into a standard normal critical value, which represents the minimum difference between measurements that needs to be exceeded to be confident that a real change has occurred.

A detailed description of the statistical formulations used to calculate the inter-observer and intra-observer ICCs (for fixed and random observers), estimate variance components and conduct hypothesis tests is provided in the paper attached as Appendix 3. The formulas used to calculate confidence intervals for the ICCs were not provided in the paper in Appendix 3, but were provided in an addendum to that paper. It is not necessary to include the formulas for these calculations in this thesis.

C1.5 A worked example and notes about the practical interpretation of the results

The formulas developed by Eliasziw and colleagues (details provided in Appendix 3) were used to determine the reliability of the screening protocols used in Chapter B3 of this thesis. The complete results of this reliability assessment are provided in the following chapters. An example is provided here, using data collected for the hip external rotation test, which was part of the musculoskeletal screening protocol. The ICC for inter-observer reliability was calculated as 0.66 (95% CI 0.25, 0.90). The SEM for this test was 5.0°. To allow clinical interpretation of this SEM, it was translated into a critical value, which was 13.8°. This means that measurements taken by two independent observers would need to be at least 13.8° apart to be considered significantly different.

The ICC for intra-observer reliability was calculated as 0.88 (95% CI 0.54, 0.86). The SEM was 3.0° and the critical value for the SEM was 8.3°. This means that measurements taken by one observer would need to be at least 8.3° apart to be confident the difference was the result of a real change.

Several classification systems or benchmarks for determining acceptable ICCs have been proposed in the reliability literature. In their paper, Eliasziw and colleagues [180] used the classifications proposed by Landis and Koch [181], which classified ICCs as:

- slight (0.00 – 0.20);
- fair (0.21 – 0.40);
- moderate (0.41 – 0.60);
- substantial (0.61 – 0.80); and
- almost perfect (0.81 – 1.00).

Therefore, using this classification system, the inter-observer reliability of the hip external rotation test would be considered substantial. The intra-observer reliability would be considered almost perfect.

To provide a comparison with the inter-observer ICCs obtained, the ICC for was calculated using the Shrout and Fleiss [182] approach that has been commonly cited in the literature. If the mean of each observer's ratings were used to calculate the inter-observer reliability using the ICC (2,1) formula of Shrout and Fleiss [183], the estimated inter-observer reliability would be 0.92, which is much higher than the ICC of 0.66 calculated using individual observations in the Eliasziw et al. method. This example demonstrates that many of the ICCs reported in the literature have been substantially inflated by determining the reliability of the mean of two measurements, and not the reliability of individual measurements. It is for this reason, that the statistical method developed by Eliasziw and colleagues should be used for the determining the reliability of screening protocols used in sports injury research. This is particularly applicable to those studies where only one measurement will be used to determine injury risk, as was the case with the study presented in Chapter B3 of this thesis.

C1.6 Summary

Sports injury prevention requires a firm evidence base. An important component of this is the accuracy and reliability of measurements taken in studies of risk factors. When measurements are not reliable, it is difficult to distinguish between participants with or without risk factors because of the large measurement error.

In this chapter, an overview of a method for the simultaneous assessment of inter- and intra-observer reliability has been provided. Unlike many other popular methods in the literature, this method is valid for the calculation of both inter-observer and intra-observer reliability in the same study. The results of using this statistical method to determine the reliability of the musculoskeletal, fitness and technique screening tools used in Chapter B3 are described in the following chapters.

C2: Reliability of the musculoskeletal screening protocol

C2.1 Introduction

Using the statistical method presented in Chapter C1, the inter- and intra-observer reliability of the musculoskeletal screening protocol used in Chapter B3 of this thesis was determined.

C2.2 Methods

The reliability assessment was conducted using two physiotherapists (observers). These were the two physiotherapists that conducted the musculoskeletal screening tests with the NSW bowlers who participated in the prospective cohort study described in Chapter B3. There were 10 participants, who were all volunteers. Five of the participants were cricketers and the remaining 5 participated regularly in other active sports. The detailed protocol used for the musculoskeletal assessment was described previously in Chapter B3 on page 151.

C2.2.1 Range of motion tests

The participants were each required to attend one appointment, in which they were tested by each observer twice (in the order of Observer 1, Observer 2, Observer 1, Observer 2). The tests were conducted in the same order each time, with 10-minute rest breaks between each session for the following tests:

- Knee extension;

- Modified Thomas Test (hip extension);
- Modified Thomas Test (hip abduction);
- Hip internal rotation;
- Hip external rotation;
- Combined elevation test; and
- Ankle dorsiflexion lunge.

As per the protocol described in Chapter B3, each observer had an assistant. The assistant recorded the measurements for each test and at the end of each session they filed the recording sheet. This was done so that the observers could not see the results of the first session when they were completing the second session.

C2.2.2 Muscular endurance tests

A different method was used to assess the reliability of the other tests in the musculoskeletal screening protocol:

- Bridging hold;
- Prone four point hold; and
- Calf heel raises.

This was due to the nature of the tests, as they are measures of muscular endurance and require maximal effort by the participant. The scores for multiple trials could be vastly different and this would result in poor inter- and intra-observer reliability results. However, these differences would not necessarily be a result of measurement error by the observer. The differences would more likely be the result of the participant being adversely affected by fatigue [184, 185] and not being physically able to complete the test four times (two trials per observer).

Therefore, rather than completing two trials with each observer, the participants only completed one trial for these muscular endurance tests. The physiotherapists both observed this single trial. A video camera was positioned side-on to the participant to record the trial (sagittal plane). The footage of these tests was later viewed by each observer to determine their scores for a second "trial", to allow the calculation of inter- and intra-observer reliability.

For the bridging hold and prone four point hold, the video camera was positioned approximately 30cm off the ground (in line with the height of the pelvis). For the calf heel raises, the video camera was attached to a tripod and set approximately 100cm off the ground.

For the four point prone hold and the bridging hold, the observers each had a stopwatch. The participant held the position for as long as possible until failure. The observers did not stop the participant during the test if they were no longer holding the correct position. Instead, they noted the time at which they would usually terminate the test. The observers did not communicate during the test and on completion of the trial, recorded their results on separate recording sheets, which were then given to their respective assistants to file.

A similar process was used for the calf heel raises. Both physiotherapists observed the trial whilst the video footage was being captured and did not stop the participant if they were no longer raising the heel through a full range with the knee extended. Instead, they noted the number of correctly completed trials. As with the four point prone hold and bridging hold tests, the observers did not communicate during the test. On completion of the trial, they recorded their results on separate recording sheets, which were then filed.

Approximately 15 minutes after the muscular endurance tests had been completed (the same time span between sessions for the range of motion tests), the observers individually reviewed the video footage. Whilst viewing the footage of the four point prone hold and bridging hold tests, they used a stopwatch to record the duration that the participants held the correct position. Similarly, with the calf heel raises, each observer individually reviewed the video footage to determine the number of heel raises completed correctly. Each observer recorded their results on a blank recording sheet and gave it to their assistant to file.

C2.3 Results

The results of the reliability assessment are presented in Tables 56 and 57.

Table 56 Inter-observer reliability of the musculoskeletal screening protocol

Screening test	Inter-observer			
	ICC	95% CI	SEM	SEM critical value
Knee extension (°)	0.40	0.00, 0.79	5.5	15.1
MTT* hip extension (°)	0.27	0.00, 0.76	6.6	18.4
MTT* hip abduction (°)	0.29	0.00, 0.71	2.5	7.2
Hip internal rotation (°)	0.30	0.00, 0.78	8.9	24.6
Hip external rotation (°)	0.66	0.25, 0.90	5.0	13.8
Ankle dorsiflexion lunge (cm)	0.96	0.89, 0.99	0.4	1.1
Combined elevation test (cm)	0.87	0.63, 0.97	1.9	5.4
Calf heel raises	0.99	0.98, 1.00	0.3	0.8
Bridging hold (sec)	0.56	0.42, 0.88	24.8	68.7
Prone four point hold (sec)	0.89	0.79, 0.97	15.7	43.6

* MTT = Modified Thomas Test

Table 57 Intra-observer reliability of the musculoskeletal screening protocol

Screening test	Intra-observer			
	ICC	95% CI	SEM	SEM critical value
Knee extension (°)	0.86	0.43, 0.95	2.6	7.2
MTT* hip extension (°)	0.97	0.84, 0.99	1.3	3.7
MTT* hip abduction (°)	0.83	0.21, 0.92	1.3	3.5
Hip internal rotation (°)	0.94	0.68, 0.97	2.7	7.5
Hip external rotation (°)	0.88	0.54, 0.96	3.0	8.3
Ankle dorsiflexion lunge (cm)	0.98	0.92, 0.99	0.3	0.8
Combined elevation test (cm)	0.97	0.88, 0.99	1.0	2.7
Calf heel raises	0.99	0.97, 1.00	0.3	0.8
Bridging hold (sec)	0.56	0.00, 0.83	24.8	68.7
Prone four point hold (sec)	0.89	0.62, 0.97	15.7	43.6

* MTT = Modified Thomas Test

Using the classification system proposed by Landis and Koch [191], the ICCs obtained for the intra-observer and inter-observer of the tests in this musculoskeletal screening protocol are presented in Tables 58 and 59, respectively.

Table 58 Classification of the intra-observer ICCs for the tests in the musculoskeletal screening protocol

	Almost perfect	Substantial	Moderate	Fair	Slight
Knee extension	✓				
MTT hip extension	✓				
MTT hip abduction	✓				
Hip internal rotation	✓				
Hip external rotation	✓				
Ankle dorsiflexion lunge	✓				
Combined elevation test	✓				
Calf heel raises	✓				
Bridging hold			✓		
Prone four point hold	✓				

Table 59 Classification of the inter-observer ICCs for the tests in the musculoskeletal screening protocol

	Almost perfect	Substantial	Moderate	Fair	Slight
Knee extension				✓	
MTT hip extension				✓	
MTT hip abduction				✓	
Hip internal rotation				✓	
Hip external rotation		✓			
Ankle dorsiflexion lunge	✓				
Combined elevation test	✓				
Calf heel raises	✓				
Bridging hold			✓		
Prone four point hold	✓				

C2.4 Discussion

As shown in Table 56, generally the intra-observer ICCs were higher than the inter-observer ICCs. This is consistent with reviews of reliability studies [191]. There are no universally applicable standards as to how high the ICC must be to constitute acceptable reliability in sports injury risk factor research. Therefore in the absence of clear guidelines, it would seem reasonable to consider those tests with reliability considered almost perfect (ICC= 0.80 – 1.00) as acceptable for the purposes of this research program.

C2.4.1 Intra-observer reliability

The musculoskeletal screening tests demonstrated excellent intra-observer reliability, with ICCs above 0.80. The majority of the tests also had low SEM critical values. The only exception was the bridging hold test, with an ICC of 0.56. It is difficult to compare these findings with previous research, as different statistical methods to determine the ICCs have been used (as described in Chapter C1). However, consistent with the findings of this study, previous studies have reported high intra-observer reliability of the Modified Thomas Test [185] and the ankle dorsiflexion lunge [185].

C2.4.2 Inter-observer reliability

The inter-observer reliability of the ankle dorsiflexion lunge, the combined elevation test, calf heel raise test and the prone four point hold was excellent. The SEM critical values demonstrated that the difference that would need to be observed between testers to be confident there was a real difference was low for the ankle dorsiflexion lunge and calf heel raise test.

The ankle dorsiflexion was the only one of these tests to have been investigated in previous research, which also reported high inter-observer reliability [185]. The remaining tests in the protocol demonstrated lower ICCs for inter-observer reliability, ranging between 0.27 and 0.66. Of these, the Modified Thomas Test demonstrated much lower inter-observer reliability than has been reported in previous research [185], which may be due to the differences in the statistical methods used to determine the ICCs.

C2.4.3 Summary

As described in Chapter C1, the majority of previous studies have used the mean of two measurements to determine ICCs. This has the effect of inflating the ICC, as the mean of multiple measurements will be higher than that based on a single measurement [192, 193]. Because of the different methods used to determine ICCs in previous research, it is not reasonable to compare the ICCs in this study with the findings of previous research due to these different statistical calculations.

With the exception of the bridging hold test, all of the tests in the musculoskeletal screening protocol demonstrated almost perfect intra-observer reliability and would be considered acceptable tests for those occasions where only one observer was conducting multiple measurements. The inter-observer reliability was generally not as high, but the ankle dorsiflexion lunge, combined elevation test, calf heel raise test and prone four point hold demonstrated almost perfect inter-observer reliability and would again be considered acceptable. This is of particular importance to the study described in Chapter B3, because a number of observers contributed measurements that were used to determine injury risk. The hip external rotation and bridging hold tests demonstrated substantial and moderate reliability respectively and the remaining tests were considered fair.

The implications of this reliability assessment for the findings of the prospective cohort study described in Chapter B3 are discussed in Part D of this thesis.

C3: Reliability of the technique analysis protocol

C3.1 Introduction

Using the statistical method presented in Chapter C1, the inter- and intra-observer reliability of the technique analysis protocol used in Chapter B3 of this thesis was determined.

C3.2 Methods

The reliability assessment was conducted using two members of the research team (observers), who were sports science graduates and had both used the siliconCOACH software to analyse the technique of fast bowlers previously. This reliability assessment focused on the observers' ability to produce the same measurements of selected parameters of the fast bowling action using siliconCOACH software. Therefore, footage that had already been captured during the baseline screenings conducted as part of the prospective cohort study was used for this reliability assessment. The detailed protocol used for the technique analysis in siliconCOACH was described previously in Chapter B3 on page 165.

C3.3 Results

The results of the reliability assessment are presented in Tables 60 and 61.

Table 60 Inter-observer reliability of the technique analysis protocol

Screening test	Inter-observer			
	ICC	**95% CI**	**SEM**	**SEM critical value**
Stride length (m)	0.85	0.69, 0.95	0.05	0.14
Front knee angle at FFI (°)	0.68	0.32, 0.89	5.56	15.41
Maximum front knee angle (°)	0.95	0.85, 0.98	2.90	8.04
Height of ball release (m)	0.90	0.78, 0.97	0.05	0.14
Ball speed (km/h)	0.90	0.76, 0.97	3.69	10.23
Shoulder angle at BFI (°)	0.96	0.89, 0.99	4.52	12.53
Minimum shoulder angle (°)	0.97	0.93, 0.99	1.73	4.80
Shoulder counter-rotation (°)	0.94	0.83, 0.98	3.98	11.03

Table 61 Intra-observer reliability of the technique analysis protocol

Screening test	Intra-observer			
	ICC	**95% CI**	**SEM**	**SEM critical value**
Stride length (m)	0.88	0.63, 0.96	0.05	0.14
Front knee angle at FFI (°)	0.89	0.63, 0.96	3.25	9.01
Maximum front knee angle (°)	0.98	0.92, 0.99	1.94	5.38
Height of ball release (m)	0.91	0.72, 0.97	0.04	0.11
Ball speed (km/h)	0.95	0.84, 0.98	2.68	7.43
Shoulder angle at BFI (°)	0.98	0.94, 0.99	3.16	8.76
Minimum shoulder angle (°)	0.97	0.91, 0.99	1.66	4.60
Shoulder counter-rotation (°)	0.98	0.92, 0.99	2.53	7.01

Some of these measures rely on the identification of the frames in which back foot impact, front foot impact and minimum shoulder angle occur in the video footage. Therefore, the consistent identification of these events is essential for the reliability of these measures.

Using side-on footage, in 80% of the trials there was exact agreement for the frame in which back foot impact occurred for Observer 1. For Observer 2, there was exact agreement for 90% of trials. For front foot impact, Observer 1and Observer 2 recorded exact agreement for 70% of the trials. All remaining trials only differed by one frame.

Using the overhead footage, in 80% of the trials there was exact agreement for the frame in which back foot impact occurred for Observer 1. For Observer 2, there was exact agreement for 90% of trials. For the time of minimum shoulder angle, Observer 1 recorded exact agreement for 50% of the trials. Observer 2 recorded exact agreement for 70% of the trials. As with the side-on footage, all remaining trials only differed by one frame.

Using the classification system described in the previous chapter, the ICCs obtained for the intra-observer and inter-observer of the tests in this technique analysis protocol are presented in Tables 62 and 63, respectively.

Table 62 Classification of the intra-observer ICCs for the tests in the technique analysis protocol

	Almost perfect	Substantial	Moderate	Fair	Slight
Stride length	✓				
Front knee angle at FFI	✓				
Maximum front knee angle	✓				
Height of ball release	✓				
Ball speed	✓				
Shoulder angle at BFI	✓				
Minimum shoulder angle	✓				
Shoulder counter-rotation	✓				

Table 63 Classification of the inter-observer ICCs for the tests in the technique analysis protocol

	Almost perfect	Substantial	Moderate	Fair	Slight
Stride length	✓				
Front knee angle at FFI		✓			
Maximum front knee angle	✓				
Height of ball release	✓				
Ball speed	✓				
Shoulder angle at BFI	✓				
Minimum shoulder angle	✓				
Shoulder counter-rotation	✓				

C3.4 Discussion

The inter- and intra-observer reliability of using siliconCOACH software to examine selected parameters of the fast bowling action has not previously been reported. This reliability assessment has demonstrated that the intra-observer reliability is excellent, with all measures being categorised as almost perfect. The inter-observer reliability was also very high. All measures, with the exception of the front knee angle at front foot impact, would be considered acceptable for use in risk factor research. The measure of front knee angle at front foot impact was categorised as substantial. The ICC for this particular measure may have been influenced by the difference in identification of the frame in which front foot impact occurred using the side-on footage.

This study did not assess the validity of using siliconCOACH software to determine selected aspects of fast bowling technique measured in this thesis. A validity assessment has previously been described by Elliott and colleagues [169].

C4: Reliability of the fitness testing protocol

C4.1 Introduction

Using the statistical method presented in Chapter C1, the inter- and intra-observer reliability of the fitness testing protocol used in Chapter B3 of this thesis was determined. The reliability of many of the tests used in the fitness and anthropometric assessment protocol had previously been established for athletes and reported in the scientific literature, including the Yo-Yo test [194] and body composition measures [193]. Therefore, a reliability assessment was only conducted for those tests for which reliability had not previously been reported.

C4.2 Methods

The reliability assessment was conducted using two members of the research team (observers), who were both sports science graduates. There were 10 participants, who were all volunteers. All participants were cricketers. The detailed protocol used for the fitness assessment was described previously in Chapter B3 on page 168.

As was described in Chapter C2 on page 220, participants may be adversely affected by fatigue when completing multiple trials of a test. This may result in differences in the scores obtained in these multiple trials. Therefore, the participants were required to attend one appointment, in which they completed only two trials of each of the tests. Each trial was measured by both of the observers. So that the observers could not establish the scores recorded by the other observer, they did not communicate during the tests.

The tests were conducted in the same order each time, with 10-minute rest breaks between each session for the following tests:

- 40m sprint;
- Vertical jump;
- Chest medicine ball throw;
- Overhead medicine ball throw; and
- Side-on medicine ball throw.

The protocols used with the NSW bowlers were used to determine the reliability of the 40m sprint and vertical jump tests (as described in Chapter B3).

The observers recorded the measurements for each test and at the end of each session they filed the recording sheet. This was done so that the observers could not see the results of the first session when they were completing the second session.

C4.3 Results

The results of the reliability assessment are presented in Tables 64 and 65.

Table 64 Inter-observer reliability of the fitness testing protocol

Screening test	Inter-observer			
	ICC	95% CI	SEM	SEM critical value
40m sprint (sec)	0.89	0.85, 0.98	0.49	1.36
Vertical jump (cm)	0.99	0.99, 1.00	1.22	3.38
Chest medicine ball throw (m)	0.95	0.93, 0.99	0.26	0.72
Overhead medicine ball throw (m)	0.91	0.88, 0.99	0.47	1.30
Side-on medicine ball throw (m)	0.85	0.80, 0.98	0.85	2.36

Table 65 Intra-observer reliability of the fitness testing protocol

Screening test	Intra-observer			
	ICC	95% CI	SEM	SEM critical value
40m sprint (sec)	0.89	0.63, 0.97	0.49	1.36
Vertical jump (cm)	0.99	0.96, 1.00	1.22	3.38
Chest medicine ball throw (m)	0.95	0.81, 0.99	0.26	0.72
Overhead medicine ball throw (m)	0.91	0.69, 0.98	0.47	1.30
Side-on medicine ball throw (m)	0.85	0.51, 0.96	0.85	2.36

Using the classification system described in the previous two chapters, the ICCs obtained for the intra-observer and inter-observer of the tests in this fitness testing protocol are presented in Tables 66 and 67, respectively.

Table 66 Classification of the intra-observer ICCs for the tests in the fitness testing protocol

	Almost perfect	Substantial	Moderate	Fair	Slight
40m sprint	✓				
Vertical jump	✓				
Chest medicine ball throw	✓				
Overhead medicine ball throw	✓				
Side-on medicine ball throw	✓				

Table 67 Classification of the inter-observer ICCs for the tests in the fitness testing protocol

	Almost perfect	Substantial	Moderate	Fair	Slight
40m sprint	✓				
Vertical jump	✓				
Chest medicine ball throw	✓				
Overhead medicine ball throw	✓				
Side-on medicine ball throw	✓				

C4.4 Discussion

As shown in Table 64, both the inter- and intra-observer reliability of the fitness testing protocols were excellent, with all tests being categorised as almost perfect and therefore being considered acceptable for use in injury risk factor research.

The possible variability in performance between trials may have caused a slight reduction in the intra-observer reliability of the fitness tests. This was because scores between trial 1 and trial 2 could be different (such as in the 40m sprint) and this would result in reduced intra-observer reliability. As was described for the muscular endurance tests in the musculoskeletal screening protocol, these differences would not necessarily be a result of measurement error by the observer. The differences would more likely be the result of the participant being adversely affected by fatigue [78, 195] and not performing at the same level for multiple trials. Nevertheless, all tests demonstrated excellent intra-observer reliability.

PART D DISCUSSION

This chapter presents a detailed discussion of the findings of the three prospective cohort studies described in Part B and the reliability assessment of the screening protocols presented in Part C. The strengths and limitations of each of these studies are also considered.

D1.1 Participating bowlers

There were a total of 305 fast bowlers recruited into the three prospective cohort studies, of whom 208 were adults (>18 years) and 97 were adolescents (aged ≤ 18 years). This sample size is a strength of this research, as it is one of the largest cohorts of fast bowlers assembled. A limitation is that the bowlers recruited were all high performance and as a result, this sample is not representative of community-level players. The injury pattern and risk factors for injury may differ according to different levels of competition and therefore it may not be possible to extrapolate the findings of this research with high performance fast bowlers to community level fast bowlers.

D1.2 Injuries reported

The focus of this thesis was on those injuries associated with repetitive microtrauma of the musculoskeletal system attributable to fast bowling. Whilst these injuries are generally referred to as ‘overuse’ injuries in the literature, within this program of research they were called ‘repetitive microtrauma’ injuries (hereafter referred to as ‘injury’, unless otherwise specified).

The rate of injury was high, with nearly half (47.9%) of the 305 bowlers participating in this program of research sustaining an injury during the respective study periods. Considering the injury rate across all three studies, the adult bowlers had a higher rate of injury (55.3%) as compared with the adolescent bowlers (32.0%).

Of all cricket injuries, low back injuries sustained by fast bowlers (including spondylolysis, spondylolisthesis, pedicle sclerosis, intervertebral disc degeneration and muscular soft tissue injuries) have received the most attention in the literature [76, 78, 183, 185, 187, 190, 196]. Consistent with this focus, the injury category with the highest frequency for both adult and adolescent fast bowlers across the three studies was lumbar injuries. When considering the combined injury data reported in the studies described in Chapters B1 and B3, 22.6% of all injuries reported by the adult fast bowlers participating in these studies were lumbar injuries. The proportion was much higher among younger fast bowlers, with lumbar injuries comprising 45.2% of all combined injuries reported by the adolescent bowlers participating in the studies described in Chapters B2 and B3. As described in the Literature Review (Chapter A2), younger bowlers may be more susceptible to lumbar injuries because their musculoskeletal systems are not fully developed [169, 194, 197, 198].

Although lumbar injuries were the most frequently occurring injury category for both adult and adolescent fast bowlers, there were a range of other injuries reported, including groin injuries, hamstring and quadriceps strains, knee injuries, shin splints and foot stress fractures. The injury category with the second highest frequency for older bowlers was side and abdominal strains, when combining the injury data for adult fast bowlers presented in Chapters B1 and B3. These side and abdominal strains represented 16.5% of all injuries reported by adult fast bowlers in these studies. In addition to the 19 side strains reported in these two studies, there were 2 injuries categorised as rib stress fractures in the study presented in Chapter B1. Interestingly, no side strains occurred to the adolescent bowlers. A side strain injury is caused by tearing the internal oblique muscle from the insertion of one of the lower ribs or costal cartilages [42, 45]. However there has been some debate as to whether some of these injuries are actually rib stress fractures, rather than muscle strains [199]. Therefore, there may in fact have been more rib stress fractures than the two that were reported in the study in B1, with some of these injuries being misclassified as side and abdominal strains. It is also worth noting that there were few upper limb injuries reported, with the injury categories within this body region representing only 8.2% of all injuries. As described in Part B, it is beyond the scope of this thesis to provide medical details for injuries and timing of injuries, however, this could be considered in future research.

In considering the strengths and limitations of the method by which injury data was collected, the prospective collection of injury data was a strength of this study. The prospective study design reduced the possibility of recall bias on the part of the person reporting injury (such as the bowler, team doctor or physiotherapist) because the injuries were reported as they occurred during the season, rather than being reported retrospectively at the end of the season. Another specific strength of the study presented in Chapter B1, was that sports doctors and physiotherapists working with the cricket teams provided information regarding injuries sustained by the fast bowlers in this study. This ensured accurate reporting of the site, nature and diagnosis of injury. This was an advantage of recruiting the state and national contracted fast bowlers, as they have direct access to excellent medical support. The medical support provided to junior squads is not as extensive, so it was not possible to use a similar method for collecting injury data in the study described in Chapter B2. Similarly, the adolescent bowlers in the study in B3 did not have access to this medical support, so to ensure that the method of injury data collection was consistent for all participants, bowlers were asked to report any injuries or conditions in their bowling logbooks. The bowlers were asked to report any injury or condition, even if unrelated to cricket, and a sports physiotherapist then contacted them to ascertain further details about the injury. This was done so that the sports physiotherapist, who is an expert in the area of cricket injury, could determine the injury diagnosis, rather than the bowlers themselves.

For all three studies, recognised experts in the area of cricket injury then reviewed the injury data and based on their review, only those injuries that were sustained as a direct result of the repetitive stress of fast bowling during the study period were included (primary injuries). However, whilst every effort was made to include only those injuries meeting these criteria, it is acknowledged that the pathogenesis of some of the injuries that were included in these studies may be attributed to other causes, including the consequences of incomplete recovery from a previous injury. It is possible for a secondary injury to develop as an accommodation to a primary injury [200]. With reference to fast bowling, this means that a fast bowler may have altered their movement patterns in response to the pain or dysfunction of another injury not meeting the inclusion criteria for this study [201]. For example, a bowler may have sustained a sprained ankle as a result of slipping over in the outfield. If they then recommenced bowling before rehabilitation of this injury was complete, they may have changed the biomechanics of their bowling action to accommodate the pain caused by the ankle injury. These altered movements cause loads to be redistributed through other joints in the body [202], possibly resulting in an increased risk of sustaining an injury to another part of the body.

Injury history was considered as a potential risk factor to a certain extent in the study described in Chapter B1, but was restricted to investigating bowling-related repetitive microtrauma injuries in the previous season only. Other injuries not related to the repetitive stress of fast bowling were not considered. These injury data were obtained from an injury surveillance system implemented by Cricket Australia and administered by team doctors and physiotherapists appointed to each of the state and Australian squads [3]. Bowlers who had sustained a bowling-related repetitive microtrauma injury in the previous season were not at a significantly increased risk of sustaining an injury in the subsequent season in the study described in Chapter B1. However, injury data were not available for the adolescent fast bowlers participating in the studies described in Chapters B2 and B3. Therefore, injury was not considered as a potential risk factor for injury in these two studies, and is therefore a limitation of these studies. Injury history could be considered for investigation as a risk factor for injury to adolescent fast bowlers in future research.

Another limitation of this study is that some of the injuries that were included may not have been the result of repetitive microtrauma and instead may have been an acute injury. Gregory has suggested that acute injuries may occur without obvious trauma, pain or loss of function occurring at the time and these injuries should not necessarily be assumed to be the result of cumulative trauma [98].

There has also been some debate in the literature as to whether all musculoskeletal tissues are subject to unrecovered deformation as a result of repetitive loading. There is evidence to support the role of cumulative microtrauma in the aetiology of injuries to bone [61, 129, 130], cartilage [126], tendon and ligament [29, 203], but the relationship with muscle strain injuries is not as well understood. Whilst some clinicians might argue the case for cumulative microtrauma being an aetiological factor in the development of muscle strain injuries, there might be others who would not necessarily subscribe to this view. Hence, it is acknowledged that the aetiology of the injuries sustained by fast bowlers is complex and that the role of cumulative trauma is not clearly established for all musculoskeletal tissues, particularly muscle.

D1.3 Bowling workload and injury risk

The following section discusses the findings of the studies that investigated bowling workload as a risk factor for injury, described in Part B of this thesis. The strengths and limitations of these studies are also considered.

D1.3.1 Adult fast bowlers (Chapter B1)

The findings of this study suggest that there were thresholds for both low and high workload, beyond which the risk of injury increased. This general trend was observed for all measures of workload, but was particularly evident when examining the average number of days between bowling occurrences. Bowlers with an average of less than 2 days, and bowlers with an average of 5 or more days between bowling occurrences, were at a significantly increased risk of injury compared with bowlers with an average of 3.0 – 3.9 days. These findings suggest that allowing sufficient rest periods between bowling sessions could be an important injury prevention strategy for fast bowlers. A similar concept was raised by Orchard and James [60], who reported a significant increase in injury risk for first-class fast bowlers when bowling in the second match of back-to-back matches (defined as < 3 day break between first-class matches or < one day break between one-day matches).

For the workload measure of bowling days per week, there was a significant increase in the risk of injury for bowlers with the highest workload, in terms of combined days (match plus training), match days only and training days only. There was also a significant increase in injury risk for bowlers with the highest average number of deliveries bowled per week. Bowlers with an average of 200 or more deliveries per week (match plus training) were at a significantly greater risk of injury, as compared with bowlers with an average of 150 – 174.9 deliveries per week. Similar trends were observed when examining match and training workload independently, but these findings were marginally non-significant, with lower CIs of 0.99 and 0.98 respectively. These findings correspond with previous research that reported a significant increase in the risk of injury for bowlers with an average weekly workload greater than 203 deliveries [60].

The findings relating to training workload in this study are particularly important, as bowling at training is the most modifiable form of workload. It may be difficult to limit match workload (especially with professional players), however training workload is much easier to moderate. The possible strategies for modifying bowling workload are discussed later in this chapter.

Whilst high workload has been identified in previous research as a risk factor for injury, it may also be possible that a certain workload is required to prevent injury and ensure the bowler is able to withstand the pressures of continued fast bowling. In the present study, it seems that maintaining a bowling workload that was too low or too infrequent was as significant a risk factor for injury as maintaining a high bowling workload. Risk of injury was significantly increased for bowlers with the most (≥ 5.0) number of days between bowling occurrences, as compared to bowlers with an average of 3.0 – 3.9 days between bowling occurrences. This was an unexpected finding of this study and further research is required to determine why bowlers with a low bowling frequency were at an increased risk of injury. A possible explanation is that there may be an ‘acquired resistance’ to injury which can be attained by bowling more frequently than once every 5 days. Hence this protective effect may be the result of exposure to an optimal level of loading, and subsequent musculoskeletal adaptations. It is also possible that confounding factors may have been responsible for this relationship. For example, bowlers with a past history of injury may be reticent to bowl frequently.

Injury history was considered as a potential risk factor in this study to a certain extent, but was restricted to investigating bowling-related repetitive microtrauma injuries in the previous season only. Other injuries not related to the repetitive stress of fast bowling were not considered. Bowlers who had sustained a bowling-related repetitive microtrauma injury in the previous season were not at a significantly increased risk of sustaining an injury in the subsequent season. However, a bowler may have sustained an injury that was not bowling-related but caused a subsequent change in the movement patterns of the bowler. As discussed earlier in this chapter, this change may have predisposed the bowler to another injury. It may also have been possible that injuries that occurred two or more seasons ago influenced the bowling behaviours of the participants in this study.

As bowling frequency was only measured in terms of bowling days in this study, future research could consider exposure time in greater detail. Fast bowling is a stressful activity on the lumbar spine as it involves cyclical loading. Following this cyclical loading of the lumbar spine, the viscoelastic structures (ligaments, discs and joint capsules) become more flexible than normal and hence allow greater intervertebral movement [60]. This may lead to a decrease in stability of the lumbar spine and pelvis, which therefore increases susceptibility to injury due to the joints being pushed beyond their safe limits of movement [29]. The rate of recovery of normal viscoelastic laxity and reflexive multifidus stabilising activity has been shown to be much slower than their decrement associated with cyclical loading [56]. In other words, it appears that it takes much longer for the spine to recover, than the actual length of time spent loading it. Therefore further investigation is needed to determine optimum fast bowling work to rest schedules. Players who bowl a lengthy spell or consecutive spells without adequate rest may be at a higher risk of injury. Information about spell length is essential in developing guidelines for safe work to rest schedules for fast bowlers, and should be the focus of future injury risk factor research.

Foster and colleagues attempted to describe the relationship between match bowling and injury by stating amongst the bowlers who bowled more than the mean number of matches (*M* = 17) for the group, 58% sustained a stress fracture or disabling injury [60]. However in the study by Foster et al., it appears that bowlers were compared according to the total number of sessions/deliveries bowled during the entire season, which may have included bowling completed after injury. If a bowler participates in less than the average number of matches for the season, this may be the result of an inability to bowl due to an injury being sustained at the start of the season. However, for those matches in which the bowler did bowl, they may have had a workload far greater than the remainder of the group. A strength of the present study was that the analysis was restricted to only include bowling completed prior to the occurrence of any injury. This was due to the importance of distinguishing between injury risk factors and factors associated with injury sequelae [116]. For example, bowlers may not bowl for a period of time following injury or may change their bowling behaviour once an injury has been sustained. For the same reasons, if a bowler sustained multiple injuries or recurrences of an injury within a season, only the workload prior to the first injury occurrence each season was reported.

A major strength of this study was the method by which bowling workload data was collected. Research assistants attended each training session throughout the study period and counted the number of deliveries bowled by each of the participants in this study. Match workload was retrieved from match scorecards. This ensured that any recall bias or other potential errors associated with asking the bowlers to self-report bowling workload were removed. Some coaches have suggested it is possible to estimate total seasonal workload (match plus training) based on match workload only, for a group of fast bowlers. Linear regression analyses demonstrated that it was possible to predict total workload from match workload only, for both deliveries and sessions. However, this method of calculating workload is highly reliant on training practices, which can change between squads as well as between seasons. The *y*-intercepts for the linear regression equations were different for each season, which means that total workload would be under-estimated or over-estimated by using one standard equation across different seasons. This method of determining workload should also be viewed with caution due to the fact that variances in workload between sessions will not be taken into account. If the risk of injury is to be assessed for daily, weekly and monthly workload, variance between sessions must be considered. Furthermore, this estimation provides no information about the number of rest days between bowling occurrences, which was identified as a risk factor for injury in this study.

Whilst this study had a number of strengths, the limitations are also acknowledged. These limitations include the absence of a measure of bowling intensity. As was described in previous research, not all deliveries recorded throughout the season would have been bowled with 100% effort [117]. Bowling speed may be a possible measure of intensity, but it is not practical to record the speed of each delivery bowled throughout the season with a radar gun. Bowlers could be asked to report the percentage effort they applied during each match and training session. But this is highly subjective and has the potential to be misreported. A fast bowler striving for selection in a state or national team may not report that they had bowled with any less than 100% effort during a session [60]. However, it is acknowledged that the intensity of bowling could potentially modify the recommendations for bowling volume and future research could consider the inclusion of a measure of bowling intensity, such as a rating of perceived exertion [60].

For the first two seasons of this study, funding was obtained to recruit 100% of the first-class fast bowlers in Australia into the study and to continue to monitor approximately 40% of the bowlers for the third season. Even so, the sample size each season was relatively small, with only approximately 70 fast bowlers per season being selected in Australian first-class squads. To increase the sample size of the study, the data for the three seasons was pooled and statistical analyses conducted on this combined data. Because some bowlers participated in the study for all three seasons and others were involved for two seasons, it is possible that the data is limited by a lack of independence. However, as discussed previously in this chapter, there was no association between injury in the previous season and an increased risk of injury in the subsequent season. This provides assurance that the approach taken, by combining the data across the three seasons, was acceptable.

Although not examined in this study, it has been proposed that the mixed bowling technique, poor physical condition and preparation, along with high bowling workload, may increase the risk of injury. Further research needs to be conducted to investigate the relationship between technique and workload to assess whether technique changes as workload increases. It has been shown that shoulder counter-rotation increased in some bowlers during a 12 over spell [119]. However, no reported research has examined whether technique significantly changes through the course of a season as a result of increasing bowling workload. There is also a need for further research to assess the effects of workload on physical characteristics such as muscle imbalances, posture and core stability deficiencies.

Other risk factors such as injury history, age at which the player commenced fast bowling, posture, anthropometric characteristics, footwear and playing surface may also play a role in the occurrence of injury. Injury occurs when an imposed load exceeds the tolerance (load-carrying ability) of a tissue [55]. However, as stated by Whiting and Zernicke, there are many other contributory factors that make this anything but a simple relation between load and injury. These include age, genetics, nutrition, physical condition, psychological status, fatigue, environment, previous injury, rehabilitation, anthropometric variability and skill level [87]. Future studies might consider a range of potential injury risk factors, but a large sample of bowlers would be required for such a comprehensive study.

Risk factors for injury are either reversible or non-reversible and whilst past injury history cannot be changed, a risk factor such as bowling workload, especially training workload, may be changed. Whilst bowling workload was examined in detail, it is important to note that the technique and physical characteristics of the bowlers in the present study may have placed them at higher or lesser risk of injury.

Whilst there were significant associations between workload and injury, it is acknowledged that workload may not have played a role in the aetiology of all injuries recorded. Workload may play a significant role in some specific injuries but not others. For example, Orchard and James have suggested that high match bowling workload seems to be particularly related to hamstring strains, side strains and shoulder injuries [46]. Continued research over a number of seasons investigating the association between workload and specific injury categories could determine which injuries are most related to workload. In the context of developing injury prevention guidelines for fast bowlers, it is not practicable to establish different workload guidelines for different injury categories. However, this additional information would allow further analysis investigating the association between workload and injury to be conducted, including only those injuries specifically related to workload. The injury thresholds established by this additional analysis could then update those suggested in this thesis. Also, as the focus of this study has been on the relationship fast bowling workload has with injury, future research may consider investigating the relationship between fast bowling workload and performance.

D1.3.2 Adolescent fast bowlers (Chapter B2)

The study presented in Chapter B1 identified a significant association between workload and injury, but the guidelines arising from this research are only applicable to adult fast bowlers. Parents and coaches should be aware that programs designed for adult fast bowlers are not necessarily appropriate for adolescents, who may be more prone to injury because their bones and ligaments are not fully developed.

As with adult fast bowlers, bowlers with fewer rest days between bowling occurrences were at a greater injury risk. Specifically, bowlers with an average of < 3.5 days between bowling occurrences were at an increased risk as compared with bowlers with 3.5 or more rest days. With regards to training workload, the risk of injury was significantly greater for bowlers with an average of < 6 days between training bowling occurrences. As described in the previous section, training workload is easier to regulate than match workload, so the findings relating to training workload are particularly important.

These findings are also of particular importance given that talented adolescent fast bowlers may be selected in a school cricket team, a district representative team, a club team, as well as the state high performance squad. The findings of this study have established the importance of moderating bowling workload. It is therefore vital that the coaches of the respective cricket squads, and parents/guardians of the bowler, ensure that the adolescent fast bowler is not subjected to an excessive workload in their attempts to meet the expectations and requirements of each individual team.

It is particularly important that bowlers consider the amount of bowling completed during training or informal practise sessions. Whilst the bowlers adhered to the match workload guidelines as listed in the Junior Cricket Policy [204] (which are enforced by umpires), in 42% of training days they exceeded the recommended number of deliveries. As has been identified in baseball, match guidelines can be enforced, but there is the potential for dramatically increased numbers of deliveries in an informal setting [204].

Fewer adolescent fast bowlers sustained a bowling-related repetitive microtrauma injury in this study than was reported for the adult fast bowlers in the study in Chapter B1 (25% vs. 58%, respectively). The rate of injury is also less than the 47% reported for South African schoolboy cricketers [204]. However, the comparability of these findings is limited, as the South African study reported injuries to bowlers in general and it is not clear what proportion of this group were fast bowlers. Furthermore, a more inclusive definition of injury was used, that included acute, trauma-related injuries, as well as overuse injuries. In a study of 70 young English fast bowlers, an injury rate of 32.8 per 100 bowlers was reported, but this study also included acute bowling injuries, such as ankle sprains [42].

Back injuries have been the focus of the majority of previous research, as they can potentially limit participation in the game for extended periods. Foster et al. reported that 38% of the 82 Australian fast bowlers in their study over one season sustained a back injury [66]. In the English junior fast bowlers study, 10% of bowlers reported back pain during the 6-month study period (3 months pre-season and the first 3 months of the season) and only one bowler sustained a stress fracture [144]. The frequency of bowlers reporting back pain (52%) and back injury (16%) in the present study differed to the results of this previous research. As the definition of injury was comparable in these two studies [144, 205], the dissimilarity in findings could be a result of differing bowling techniques, physical characteristics or workloads of the participants. Foster and colleagues found that both bowling technique and high workload were associated with injury, with 59% of the participants who bowled more than the mean number of matches for the group suffering a back injury, as compared with the overall back injury frequency of 38% [101]. In comparison, the English study found there was no increased injury risk in those that bowled the most [60]. However, in both prior studies, it appears that bowlers were compared according to the total number of sessions/deliveries bowled during the entire 6-month study period, which may include bowling completed after injury. The disadvantages of using this approach were described earlier in this Discussion chapter.

Another factor limiting direct comparison of the results of this study with the English junior study, is that the latter examined workload and injury in three months of preseason training and the first three months of the season, whilst this study monitored the 6-month cricket season [60]. As was noted by the authors of the English study [36], injuries can become manifest after the study period, which in their case was the second half of the season. In the present study, 45.5% of all injuries occurred during that period. Therefore it is possible that the English study found no relationship between injury risk and bowling workload because injuries may have occurred in the second half of the season, by which time the opportunity to bowl in matches (and bowling workload) would have increased greatly. However, it is also acknowledged that unless bowlers are monitored all year, or for subsequent seasons, injuries may become manifest after any selected study period. Continued research could investigate annual bowling workload and injury risk, by monitoring off-season and pre-season bowling in addition to workload completed during the 6-month cricket season.

One of the strengths of this study was the accurate reporting of bowling workload data. Unlike the study with adult fast bowlers described in this thesis, research assistants did not collect bowling workload data for the participants due to the extensive costs associated with employing staff. The bowlers were asked to keep detailed daily bowling workload logbooks and submit these on a weekly basis. The validity of these logbooks was extremely high, as indicated by the high level of agreement between the workload reported by the bowlers and an independent assessment by a member of the research team. This demonstrates that workload logbooks provide an accurate means by which to collect bowling workload data.

Whilst this study has contributed important information, the limitations are also recognised. As was described for the study with adult bowlers, the intensity of bowling was not considered and it is acknowledged that not all deliveries recorded during the season would have been bowled at full pace. Furthermore, to allow comparison with the existing bowling workload guidelines, bowling workload was only measured in terms of days bowled, rather than the actual duration of bowling spells and time between spells. Future research could consider rest periods and optimal fast bowling work to rest schedules in greater detail. As with the study with adult fast bowlers, bowling workload was the only potential risk factor investigated and it is acknowledged that bowling workload may not have been an aetiological factor for all injuries recorded.

Another limitation of this study was that the small sample size resulted in a lack of power to detect small to moderate differences in the bowling workload of injured and uninjured bowlers. It was also not possible to stratify the analysis according to age group because of the small sample size and this study is therefore limited in its ability to propose changes in the current Cricket Australia bowling workload guidelines for specific age groups. However, given the importance of bowling frequency, it does seem that rest days should be added to the guidelines. The results indicated that bowling more frequently than every 3.5 days (on average during the season) significantly increased injury risk.

Continued research with a larger sample may provide more detailed information about the possible injury risk with under-bowling and over-bowling, as was provided for adult fast bowlers in the study described in Chapter B1. Baseball studies have shown that a high number of pitches thrown in games increases the risk of shoulder and elbow pain for junior pitchers [147, 206]. Whilst pitching limits were proposed for games (per game and per season), the researchers stated that infrequent competitive pitching could be detrimental to a junior pitcher's development. They argued that pitching, throwing and practice drills are essential if a pitcher is to develop coordination, strength and flexibility to succeed as a junior pitcher, but also as a potential professional pitcher in future years. This supports the concept of the u-shaped risk of injury curve that was reported in the study of adult fast bowlers. Lyman and colleagues stated that a pitcher's safe and successful development involves maintaining a fine line between use and overuse [32]. Although the mechanics of baseball pitching and cricket fast bowling are different, a similar concept may exist for adolescent fast bowlers. Ideally, future research could jointly consider the influence of high and low bowling volume on skill acquisition and injury risk for adolescent fast bowlers. It may be necessary for bowlers to bowl for a minimum number of days per week or deliveries per day to ensure sufficient acquisition of the skills associated with fast bowling. However, the risk of injury must also be considered.

Similar risk factors may need to be weighted differently across different age groups because of the anatomical and physiological differences between adolescents and adults. Future research may be able to determine if high bowling workload is a more potent risk factor for injury to adolescent fast bowlers as compared with adult fast bowlers. This continued research could also investigate whether it is appropriate for bowling workload guidelines for adolescent fast bowlers to be determined by chronological age. It may be more suitable to include a measure of the developmental stage of the adolescent fast bowler, such as the Risser stages of spinal development [47].

D1.3.3 Adolescent and adult fast bowlers (Chapter B3)

The study of adolescent fast bowlers described in Chapter B2 demonstrated that bowling workload logbooks were an accurate method to collect bowling workload data. Due to the success of using bowling workload logbooks, this method was also adopted in the third study of this research program (described in Chapter B3). However, the response to the workload logbooks in this study was very poor. Fewer than half of the bowlers participating in the study provided any workload information during the course of the season and of those that did, many only provided workload data for a limited number of sessions at the start of the season. As it was not possible to retrieve this information from other sources, bowling workload was not considered in the analysis. This is a major limitation of this study and prevented the inclusion of bowling workload data in the multivariate analyses.

It is possible that the workload diaries would have been more successful with additional encouragement by the coaches, managers and medical staff associated with the high performance squads. Bowling workload was identified as a risk factor for injury for both adult and adolescent fast bowlers in the studies described in Chapters B1 and B2, which therefore establishes the importance of all fast bowlers monitoring their bowling workloads on an ongoing basis. Talented fast bowlers may be exposed to excessive bowling workloads whilst attempting to meet the requirements of their various club and representative cricket squads. It is therefore vital that cricket administrators, coaches, managers and medical staff reinforce the importance of fast bowlers keeping a record of their bowling workload. This workload should be reported back to the high performance coaches regularly. Perhaps a condition of selection in a high performance squad could be that bowlers are required to submit a bowling workload diary to their coach at the commencement of each training session. This will assist with data collection for future research projects, but perhaps more importantly, the ongoing efforts to reduce injury risk.

D1.4 Reliability of screening protocols

A limitation of previous risk factor studies reported in the cricket literature is that many have used specialised equipment and facilities to test fast bowlers, and the degree to which the testing procedures can be adopted in the cricket “real world” is unclear. However, it is vital that these field-based screening protocols are reliable. Poor reliability limits the ability of researchers to reach conclusions about whether a measured variable is indeed a risk factor for injury, because it is difficult to differentiate participants with or without the variable of interest in the presence of large random measurement error [42]. Hence, before discussing the findings of the study described in Chapter B3, in which a range of potential risk factors for injury were investigated, it is pertinent to discuss the findings of the reliability assessment of the screening protocols used in this study.

The reliability assessment selected a method for concurrently determining the inter- and intra-observer reliability of the protocols. This was an important stage of the overall program of research described in this thesis, as some previous research had used statistical calculations which resulted in the ICCs being inflated.

The reliability assessment of the musculoskeletal screening protocol showed that the tests all had excellent intra-observer reliability, with the only exception being the bridging hold test. However, the inter-observer reliability was not as high, with only 4 of the tests recording an ICC greater than 0.80 and therefore being considered acceptable. These tests were the ankle dorsiflexion lunge, the combined elevation test, calf heel raise test and the prone four point hold.

A limitation of the reliability assessment of the musculoskeletal screening protocol was that the two physiotherapists that conducted that testing for the prospective cohort study described in Chapter B3 acted as the observers in the reliability assessment. During the course of conducting the tests for the prospective cohort study (which was conducted prior to the reliability assessment), these two physiotherapists had been able to discuss the protocol in detail and were very familiar with the testing procedures. This may have resulted in higher reliability scores than may have been seen if different physiotherapists were involved in the reliability assessment. There were significant differences in the mean scores of the NSW and Queensland bowlers for many of the musculoskeletal screening tests in the study described in Chapter B3 (as listed in Table 49). Ideally, the reliability assessment would have been conducted with one physiotherapist from NSW and one from Queensland, so that they were not familiar with the way in which each other conducted the tests. However, it was not possible for the same group of 10 participants to be tested by physiotherapists from each state. Future reliability assessments could recruit physiotherapists that had not had the opportunity to work together previously, to determine the reliability of the musculoskeletal screening tests.

This would ensure the physiotherapists were more representative of the broader population and provide a more realistic assessment of the reliability of the protocol.

All tests in the technique analysis protocol demonstrated excellent inter- and intra-observer reliability, with the exception of the measure of front knee angle at front foot impact. This is the only test not to be considered acceptable. Finally, all the tests in the fitness testing protocol demonstrated almost perfect inter- and intra-observer reliability and are therefore considered acceptable.

A limitation of the reliability assessment was that a small number of participants were recruited. This is not dissimilar to previous reliability studies that have only enrolled 10 – 20 participants, as presented in Table 55. The validity of the tests included in the screening protocols was not assessed, but were based on well established clinical and field assessment tools for use with athletes. However, future research may consider the validity of these tests, in addition to the inter- and intra-observer reliability. Given that many of the tests included in the musculoskeletal screening protocol demonstrated low inter-observer reliability, further studies could endeavour to identify reliable field-based tests for ongoing use with fast bowlers. It may also be possible that only those tests conducted in a laboratory are able to provide both valid and reliable information for fast bowlers and that it is simply not possible to assess these measures in a field-based environment.

The main limitation of this reliability assessment was that it was conducted after the baseline screenings for the prospective cohort study described in Chapter

B3 had been completed. As described earlier in this thesis, ideally a reliability study should be conducted prior to commencement of baseline screenings. The findings of this reliability assessment should then inform the selection of the tests for inclusion in the final screening protocols. However, due to time constraints, it was not possible to conduct a reliability assessment before the prospective study commenced. It is acknowledged that this resulted in some tests being included in the protocol for the study described in Chapter B3, for which the reliability was questionable. This issue is discussed further in section D1.5.

D1.5 Physical characteristics, bowling technique and injury risk

The primary aim of the study presented in Chapter B3 was to investigate bowling workload, technique and physical characteristics as potential risk factors for injury. As described previously, a lack of data prevented bowling workload from being considered. However, a range of measures relating to bowling technique and physical characteristics were collected and analyses were conducted to investigate the association between these factors and injury.

After following a standard process of statistical model building, multivariate analysis identified the measures of hip rotation and ankle dorsiflexion as independent predictors of back, trunk and lower limb injuries, after adjusting for the effect of state squad. Reduced hip internal rotation on the bowling side of the body (back foot impact leg) was associated with a significantly decreased risk of injury. Reduced ankle dorsiflexion on the non-bowling side of the body (front foot impact leg) was associated with a significantly increased risk of injury.

Before discussing these two injury risk factors in detail, it must be acknowledged that the reliability of the protocols used in the baseline screening may have influenced these results. Poor reliability makes it difficult to ascertain whether a measured variable is indeed a risk factor for injury. In regards to the tests conducted to collect information about hip internal rotation and ankle dorsiflexion, the ankle dorsiflexion lunge test demonstrated excellent inter- and intra-observer reliability. The SEM critical values were also quite low for both inter- and intra-observer reliability. The inter-rater reliability is of particular importance within the context of this study, as measurements determined by different observers were used to assess injury risk. The reliability assessment determined that the SEM critical value for the ankle dorsiflexion lunge test was 1.1cm. This means that measurements taken by two independent observers would need to be at least 1.1cm apart to be considered significantly different.

Whilst the intra-observer reliability of the hip internal rotation test was also excellent, the inter-observer reliability was very low, with an ICC of 0.30 and a SEM critical value of 24.6°. These results mean that the measurements of hip internal rotation determined by different observers were not consistent. This is a major limitation of the findings of the study presented in Chapter B3, because these measurements of hip rotation were used to assess injury risk. Essentially, this demonstrates that where at all possible, future studies should conduct a reliability assessment before commencing a prospective cohort study. This will ensure that the concerns described above do not arise. It may also be necessary to adopt a different protocol for measuring hip rotation, such as the active test used by Gabbe and colleagues [47].

One of the significant measures in the study described in Chapter B3 was potentially limited by poor reliability. Conversely, it may be possible that some of the measures that were not identified as independent injury risk factors were also limited by poor reliability. Some of the non-significant measures may actually be injury risk factors, but poor reliability limited the ability of this association to be identified in study B3. Furthermore, the field-based screening protocols may not have provided the same level of accuracy afforded by laboratory based tests. Previous research has reported a consistent association between the mixed bowling technique and injury. However, none of the technique measures in this study were significantly associated with injury. This may be due to limitations of using a two dimensional analysis of bowling technique and that the tests used in the study in B3 were simply not valid as predictors of injury risk. It is acknowledged that some joint axes of flexion-extension were not exactly perpendicular to the sagittal plane filmed [42]. For example, angles of the knee observed by a side-on camera will not correspond to the true joint angle, because the movement does not occur exactly in the plane perpendicular to the camera axis (parallax error). It is possible, although unlikely given the results of previous research, that the elite fast bowlers who participated in this study had already corrected any technique faults due to their higher level of coaching.

The study described in Chapter B3 may have been limited by sample size and significant associations may have been identified with a larger sample of fast bowlers. Whilst all available fast bowlers in the high performance squads for the NSW and Queensland cricket associations were recruited, it perhaps would be necessary to monitor bowlers from all six state squads around Australia. A larger sample could provide additional power to detect differences between the injured and uninjured bowlers for the factors measured in the baseline screenings. However, substantial research funding would be required to conduct such a comprehensive study.

Another potential limitation of this study is the inclusion of a diverse range of repetitive microtrauma injuries, including injuries affecting the tissues of bone, ligaments, tendons, cartilage and muscle. The risk factors and mechanisms for these injuries will not necessarily be universal. This may have contributed to a limited number of significant independent risk factors for injury being identified. As was identified by Gabbe and colleagues in a study investigating predictors of lower limb injury to Australian football players, this heterogeneity of injury may have prevented the identification of relevant risk factors. In this Australian football study, few independent injury risk factors were identified, with none demonstrating significant RRs [47]. The authors suggested that it would be unlikely that the wide range of injuries reported would have the same set of risk factors, and perhaps by combining the injuries in the analysis it has resulted in masking potentially important risk factors for individual injury types [42]. The study presented in Chapter B3 may have been limited by the same concept, whereby the tests used in the baseline screening protocol did not measure factors that were universally applicable to all the injuries sustained. Future research could focus on identifying risk factors for specific injury types or categories. This will only be possible with a much larger sample of fast bowlers.

In acknowledging the potential limitations of the study described in Chapter B3, two independent predictors of injury were identified in this study. The following sections provide a detailed discussion of the possible mechanisms by which ankle dorsiflexion and hip internal rotation increase the risk of injury. It is however acknowledged that the issues pertaining to reliability mean that the hip rotation finding should particularly be considered cautiously.

D1.5.1 Ankle dorsiflexion and injury risk

The range of ankle dorsiflexion has been investigated in several studies as a potential risk factor for injury [47, 207, 208]. Using the same method of measuring ankle dorsiflexion as the present study, Gabbe and colleagues found the range of dorsiflexion was significantly associated with sustaining a lower extremity injury in a group of non-elite Australian footballers [130]. The most flexible players (lunge ≥ 13 cm) were significantly less likely to sustain a lower extremity injury (RR = 0.63)[79]. However, despite a significant univariate association, the range of ankle dorsiflexion was not identified by multivariate analyses as an independent predictor of injury.

Tabrizi et al. found a strong association between a decreased range of ankle dorsiflexion (measured in a non weight-bearing position) and ankle injury in a case-control study of children [78]. Another case-control study by Hughes found that soldiers with decreased passive ankle dorsiflexion (measured in a non weight-bearing position) were 4.6 times more likely to develop metatarsal stress fractures [164]. Prospective research by Lun and colleagues measured passive ankle dosiflexion with the knee extended in a group of recreational runners and found that decreased ankle dorsiflexion was a risk factor for the development of patellofemoral pain syndrome, but not for other lower limb injuries [209].

Whilst these studies reported an association between ankle dorsiflexion and injury, other studies have not found this same association. Yates et al. examined the range of ankle dorsiflexion range of naval recruits in a non weight-bearing position as a risk factor for the development of medial tibial stress syndrome (MTSS), but unlike other studies, found that a lack of ankle dorsiflexion in knee extension or knee flexion was not a risk factor for development of MTSS [209]. Similarly, Burne and colleagues examined the range of active ankle dorsiflexion as a risk factor for the development of exertional medial tibial pain (EMTP) in a military setting and reported that the range of ankle dorsiflexion was not associated with incidence of EMTP in this study [210].

It has been suggested that athletes with restriction of dorsiflexion often compensate by excessively pronating the foot in weight bearing [209, 211, 212]. This can result in changes in the kinetics and kinematics of the lower extremity and predispose the athlete to injury [213, 214]. It has also been hypothesised that decreased ankle dorsiflexion secondary to calf tightness decreases the protective effect of calf flexibility against injury and that loading in the presence of a tight calf muscle causes a less gradual absorption of energy and an increased risk of injury [209]. It may be that in itself, a decreased range of ankle dorsiflexion is not an independent risk factor for injury, but the compensatory effects it causes may be of more significance [209].

When considering this with reference to fast bowling, a lack of ankle dorsiflexion on the non-bowling side of the body (front foot impact leg) can possibly relate to injury to fast bowlers in a number of ways. Firstly, tight calf musculature in the presence of a lack of ankle dorsiflexion could render the lower limb less able to cope with the high ground reaction forces encountered at front foot impact. Compromised function of the calf muscle could increase load on the knee and patellar tendon via the closed kinetic chain [213]. Secondly, it is possible that decreased ankle dorsiflexion will result in changes in tibial and femoral alignment which have been speculated to cause changes in optimal pelvis and lumbar spine alignment in weight-bearing [214]. However, only detailed biomechanical research will be able to provide evidence for these proposed injury mechanisms. The effects of ankle range of motion on the internal loads in the lower limb could be considered in further studies.

D1.5.2 Hip internal rotation and injury risk

It has been hypothesised that a lack, or excessive amount of, hip rotation can be a risk factor for injury. The range of rotation of the hip has been investigated in several studies as a risk factor for injury [210-212, 215].

In addition to examining ankle dorsiflexion, Burne and colleagues also investigated the range of hip internal and external rotation as a risk factor for the development of EMTP [216]. Hip rotation was tested passively with the hip and knee flexed at 90º flexion in a supine position. While male subjects with EMTP had significantly increased range of hip internal rotation and hip external rotation, female subjects with EMTP did not show this relationship [214].

In a cross sectional study of professional golfers, Vad et al. [215] found a significant relationship between internal rotation movement deficit in the lead hip and a history of low back pain. A similar study of professional tennis players also found a significant relationship between lead hip internal rotation movement deficit and symptomatic low back pain [217]. However, in both of these studies the authors did not specify whether the hip was in flexion or extension or whether the testing was performed actively or passively.

In addition to examining ankle dorsiflexion, Lun et al. also investigated the range of hip internal and external rotation as a risk factor for injury in recreational runners [213]. No relationship between range of hip rotation and injury was found. It should be taken into account that with the conflicting conclusions from the above studies, the specific movement demands of different sports may predispose athletes to different patterns of injury.

Excessive internal rotation of the hip measured passively in prone has been shown to significantly lower gluteus medius and vastus medialis activity, as measured by electromyography (EMG) during a combined hip abduction and external rotation exercise [155]. Based on known lower limb mechanics, vastus medialis functions to dynamically stabilise the patella and gluteus medius functions to stabilise the hip joint in weight-bearing [162]. The results of this study by Nyland and colleagues suggest that those with increased hip internal rotation would have decreased dynamic hip and knee control contributions from gluteus medius and vastus medialis muscle activation [217].

The mechanism by which decreased hip internal rotation on the bowling side of the body (back foot impact leg) is related to a decreased risk of injury to fast bowlers is not clear. Excessive femoral internal rotation has been speculated to cause changes in optimal pelvis and lumbar spine alignment in weight-bearing which may predispose the lumbar spine to injury [211]. If decreased activation of gluteus medius is a result of increased hip internal rotation, then this may contribute to the collapse of the back leg after back foot impact, which has been reported anecdotally with some fast bowlers. However, as was described for ankle dorsiflexion, further detailed biomechanical research will be able to provide evidence for these proposed injury mechanisms. Biomechanical research could also investigate whether the field-based screening measure of hip rotation accurately reflects the rotation that occurs dynamically at certain stages of the delivery, such as at back foot impact.

D1.6 Summary

The three prospective cohort studies conducted in this program of research have contributed significantly to the international body of knowledge of risk factors for injury to cricket fast bowlers. As such, the studies have provided unique and valuable information for the development of evidence-based injury prevention guidelines for adolescent and adult fast bowlers.

The study described in Chapter B1 was the first published study to identify both low and high bowling workload as a risk factor for injury to fast bowlers. This study identified a ‘u’ shaped trend for the association between bowling workload and injury to adult fast bowlers, and has determined thresholds for workload beyond which the risk of injury significantly increases. This has allowed the development of specific guidelines for adult fast bowlers, which are summarised in section E1.2.1 on page 273.

The study in described in Chapter B2 was the first published study to monitor the workload of adolescent fast bowlers during an entire season, measuring both sessions and deliveries. This study identified an association between high bowling workload and an increased risk of injury and has contributed information for evidence-based workload guidelines for adolescent fast bowlers, which are summarised in section E1.2.2 on page 275.

Finally, the study presented in Chapter B3 collected information regarding a wide range of potential injury risk factors and identified two independent risk factors for injury: decreased range of ankle dorsiflexion on the non-bowling side of the body, and increased range of hip internal rotation on the bowling side of the body. These findings have established priority areas for future biomechanical research to investigate the mechanisms by which these factors increase injury risk.

Recommendations for how these findings can be considered in the development of injury prevention strategies for adolescent and adult fast bowlers are presented in Part E.

PART E SUMMARY, RECOMMENDATIONS AND CONCLUSIONS

E1.1 Thesis summary

Injury surveillance conducted in Australia and internationally has consistently identified fast bowlers as the cricket players at the greatest risk of injury and clearly established fast bowlers as the priority group for further research to identify risk factors for injury. Whilst previous studies have helped identify the technique, physical characteristics and workload factors related to injury to fast bowlers, cross-sectional and retrospective study designs have limited their ability to establish cause-effect relationships between the risk factors and injury. Therefore, the prospective research described in this thesis was essential to further elucidate the injury risk factors for both adolescent and adult fast bowlers and provide the information necessary for developing injury prevention strategies for fast bowlers.

There are several parts to this thesis: Part A presented the Introduction, including the aims of the thesis and specific research questions to be answered, and the Literature Review. The Literature Review provided information about epidemiological study designs, conceptual frameworks and injury prevention models, the current level of knowledge regarding injury to fast bowlers, and summarised how these concepts were considered in developing the program of research described in this thesis. Part B described the three prospective cohort studies that investigated bowling workload, physical characteristics and bowling technique as risk factors for repetitive microtrauma injury to fast bowlers. Part C described a statistical method for concurrently determining the inter- and intra-observer reliability of screening tools used in Part B, as well as presenting the results of these assessments. Finally, Part D provided a detailed discussion of the results, strengths and limitations of the studies described in Part B and the reliability assessments in Part C.

E1.2 Recommendations for bowling workload

E1.2.1 Adult fast bowlers

The study described in Chapter B1 investigated bowling workload as a risk factor for repetitive microtrauma injury to adult fast bowlers. This study identified a trend towards a dual, bidirectional threshold for workload, beyond which the risk of injury increased. Recommendations for fast bowlers with respect to bowling workload (on average during the course of a season) based on the results of this study are described below. Results relate to combined bowling workload (match plus training), unless otherwise specified. It must be noted that these recommendations are applicable only to adult, elite fast bowlers.

- **Rest days between bowling occurrences:**
    - An average of 2 or more, but less than 5 days between bowling occurrences.
    - For match workload only, an average of 3 or more days between match bowling occurrences.
- **Number of bowling days per week:**

- An average of 2 or more *, but less than 3.5 bowling days per week.

- For training workload only, an average of less than 1.8 training days per week.

- For match workload only, an average of 1.5 or more *, but less than 3 match days per week.

- **Number of deliveries per day:**

  - For training workload only, an average of more than 35 deliveries per training session (but within the limits of the recommended number of deliveries per week described below).

- **Number of deliveries per week:**

  - An average of less than 200 deliveries per week.

  - For training workload only, an average less than 70 * deliveries per week.

  - For match workload only, an average less than 175 * deliveries per week.

* the results marked with an asterisk were not statistically significant as the confidence intervals included 1.0. However, the results were clinically relevant, as the RR indicated a trend towards an increased risk of injury, with a lower bound of ≥ 0.98 for the 95% CI

E1.2.2 Adolescent fast bowlers

The study described in Chapter B2 investigated bowling workload as a risk factor for repetitive microtrauma injury to adolescent fast bowlers. This study identified high bowling workload as a risk factor for injury. Recommendations for bowling workload (on average during the course of a season) are listed below. These recommendations are only applicable to adolescent, elite fast bowlers.

- **Rest days between bowling occurrences:**
    - An average of 3.5 or more days between bowling occurrences.
    - For training workload only, an average of 6 or more days between training bowling occurrences.
    - For match workload only, an average of 7 or more days between match bowling occurrences.

E1.2.3 Possible strategies to modify bowling workload

The findings of the studies presented in Chapter B1 and B2 demonstrated an association between bowling workload and injury for both match and training workload. Of particular significance are the implications of allowing a sufficient number of rest days between bowling occurrences. In the broader sports injury literature, the role of errors in the frequency, volume, and intensity of training, in contributing to an increased risk of injury, have been identified [121]. Outerbridge and Micheli have suggested that overuse injuries can occur when an athlete increases the volume or intensity of training too quickly and the proper adaptation of the musculoskeletal tissues involved has not had time to take place [157]. Although variations in the frequency, intensity and duration of training are necessary to improve performance, the importance of rest can be overlooked [210, 211]. In proposing ways in which workload can be modified, it is important to also consider the principles of progression and overload, whereby the bowler must bowl enough in training to prevent stress injury and breakdown in match play [211].

As described in section D1.3.3 on page 258, it is vital that cricket administrators, coaches and managers emphasise the importance of monitoring and reporting bowling workload to the fast bowlers under their supervision. Rather than workload diaries being an optional contribution, they should become a mandatory aspect of participation in a high performance cricket squad.

Possible strategies for modifying bowling workload and thereby reducing the risk of injury could be considering the schedule of matches for the upcoming days and weeks and developing a plan for participation. For example, when a higher level representative match is approaching, bowlers could be rested for lower level matches, such as club cricket.

Another solution may be to increase the number of fast bowlers selected in squads and rotate these bowlers in matches. This concept has been the subject of debate among coaches, bowlers and administrators [157]. Some international fast bowlers and coaches have advocated the implementation of a rotation policy [121, 210]. Other players have suggested it would be more appropriate to consider other management strategies, such as how bowlers are used in periods where an increased number of matches are scheduled [218]. Additional rest days could be scheduled in between matches. Another possible strategy is to reduce training workload during periods of high match bowling workload, or provide additional recovery sessions to possibly reduce the risk of injury. Conversely, other coaches have suggested that fast bowlers are already under-bowled and that they should not be subject to further restrictions of their bowling workload [218]. In considering the development of injury prevention strategies, it needs to be considered whether these strategies will impinge on the basic nature and tradition of the sport of cricket and the performance of fast bowlers [217]. It is important that future research considers the effects of modifying bowling workload on the skill acquisition and performance of both adolescent and adult fast bowlers.

Whilst fast bowling workload restrictions may contribute to a reduction in the risk of injury associated with high bowling workload, there are obvious limitations associated with introducing restrictions. Limiting bowling at training may have a detrimental effect on the skill acquisition of batsmen, as they have reduced exposure to pace bowlers at training and are not adequately prepared when facing them during a match situation. Whilst a solution to this may be to introduce other talented fast bowlers to serve as net bowlers during training sessions, this merely shifts a large workload to another group of bowlers and therefore places them at an increased risk of injury. Bowling machines may sometimes provide the opportunity for increased practise for batsmen, without creating excessive workloads for fast bowlers.

As described previously, bowling completed during training is the most modifiable form of workload. However, reducing training workload may actually place a fast bowler at a higher risk of injury when bowling during a match session, as they may not be adequately prepared physically to withstand the intensity of match bowling. The objective of injury prevention strategies is to ensure that tissue adaptation stimulated from exposure to load keeps pace with, and ideally exceeds, the accumulated tissue damage [74]. Thus exposure to load is necessary but in the process of accumulating microtrauma, the applied loads must be removed to allow the healing-adaptation process to gradually increase the failure tolerance to the necessary level [74]. Tissue loading, and the risk of injury forms an optimum 'u' shaped relationship, with a safety optimum for individual tissue loading [61]. This 'u' shaped trend was observed in the study in Chapter B1 and therefore provides the ideal opportunity to consider these concepts of optimal loading for fast bowlers.

E1.3 Recommendations for physical preparation

The study described in Chapter B3 considered a range of potential risk factors for injury. This study was limited by a lack of bowling workload data, but was able to investigate measures of bowling technique and physical characteristics as risk factors for repetitive microtrauma injury. Multivariate analyses identified two independent predictors of back, trunk and lower limb injuries, after adjusting for the effect of state squad: hip internal rotation and ankle dorsiflexion.

Decreased hip internal rotation (≤ 30°) on the bowling side of the body (back foot impact leg) was associated with a significantly decreased risk of injury.

Reduced ankle dorsiflexion (<14cm) on the non-bowling side of the body (front foot impact leg) was associated with a significantly increased risk of injury. As described in section D1.5, the hip internal rotation finding needs to be considered with some degree of caution, as the test used to measure hip internal rotation demonstrated low inter-observer reliability. On the other hand, the test used to measure ankle dorsiflexion demonstrated excellent inter-observer reliability.

Based on these findings, it is recommended that fast bowlers ensure they do not have a limited range of ankle dorsiflexion. Stretching of the calf muscle group is a common intervention to help improve range of ankle dorsiflexion. Despite this, little evidence for the optimal duration and frequency of stretching to improve joint range of motion is available in the literature [74]. It has been suggested that until evidence for the contrary has been provided, a program of gastrocnemius and soleus stretching should be conducted, under the supervision of a physiotherapist or exercise physiologist, where the range of ankle dorsiflexion assessed by the lunge test is found to be restricted [108].

The mechanism by which decreased hip internal rotation is associated with a decreased risk of injury is unclear. However, increased hip internal rotation may be an indicator of inadequate gluteus medius control [219]. To redress this issue, bowlers with excessive internal rotation of the hip could undertake a program of gluteus medius strength and control exercises. Detailed biomechanical research may identify the mechanisms by which reduced ankle dorsiflexion and increased hip internal rotation contribute to the aetiology of repetitive microtrauma injuries in fast bowlers.

E1.4 Concluding statement

Sports injury prevention can be considered a staged process: determining the extent of the injury problem, developing an understanding of the specific risk factors and mechanisms of injury, developing preventive measures, evaluating these interventions, developing implementation strategies and then evaluating the effectiveness of these interventions in the implementation context [220]. Governing bodies in cricket must demonstrate that they have identified the potential injury risks for fast bowlers and have implemented appropriate measures to control these risks [221]. The program of research described in this thesis has provided considerable new information regarding risk factors for injury to fast bowlers. Whilst the identification of injury risk factors for adolescent and adult fast bowlers is important, it does not in itself lead to reductions in injury. Biomechanical research should be conducted to establish the mechanisms by which the identified risk factors contribute to the aetiology of repetitive microtrauma injuries. Reductions in injury can then be achieved by the identification and implementation of measures that control the level of exposure to and/or the consequences from these risks [219]. This is the next crucial stage in implementing successful injury prevention strategies for fast bowlers in cricket.

PART F REFERENCES

1. Rundell, M. (1995). *The dictionary of cricket* (2nd ed.). Melbourne, Australia: Oxford University Press.
2. Mar, D. (2002). *An explanation of cricket: Rules and game play described for novices.* Retrieved 22 February, 2005, from http://aus.cricinfo.com/link_to_database/ABOUT_CRICKET/EXPLANATION/EXPLANATION_OF_CRICKET.html
3. Portus, M., Mason, B.R., Elliott, B.C., Pfitzner, M.C. and Done, R.P. (2004). Technique factors related to ball release speed and trunk injuries in high performance cricket fast bowlers. *Sports Biomechanics, 3*(2), 263-284.
4. Bartlett, R.M., Stockill, N.P., Elliott, B.C. and Burnett, A.F. (1996). The biomechanics of fast bowling in men's cricket: A review. *Journal of Sports Sciences, 14*(5), 403-424.
5. Morrison, I. (1993). *Cricket: Play the game*. London, UK: Blandford.
6. Commonwealth Department of Health and Family Services and Australian Institute of Health and Welfare. (1998). *National Health Priority Areas Report: Injury Prevention and Control 1997*. Canberra, Australia: Commonwealth Department of Health and Family Services and Australian Institute of Health and Welfare.
7. Kreisfeld, R., Newson, R. and Harrison, J. (2004). *Injury deaths, Australia 2002*. Adelaide, Australia: Australian Institute of Health and Welfare.

8. Bordeaux, S. (1997). *Injury Mortality Australia 1997*. Adelaide, Australia: Australian Institute of Health and Welfare National Injury Surveillance Unit.

9. Australian Institute of Health and Welfare. (2004). *Health system expenditure on disease and injury in Australia, 2000-01*. Canberra, Australia: Australian Institute of Health and Welfare.

10. Commonwealth Department of Human Services and Health. (1994). *Better health outcomes for Australians. National goals, targets and strategies for better health outcomes into the next century*. Canberra, Australia: Australian Government Publishing Service.

11. Strategic Injury Prevention Partnership. (2001). *National injury prevention plan: Priorities for 2001-2003*. Canberra, Australia: Department of Health and Aged Care.

12. Finch, C. and McGrath, A. (1997). *SportSafe Australia: A national sports safety framework. A report prepared for the Australian Sports Injury Prevention Taskforce*. Canberra, Australia: Australian Sports Commission.

13. Egger, G. (1991). Sports injuries in Australia: causes, cost and prevention. *Health Promotion Journal of Australia, 1*(2), 28-33.

14. Medibank Private. (2004). *Sports injuries report 2004*. Melbourne, Australia: Medibank Private.

15. Australian Bureau of Statistics. (2003). *Participation in sport and physical activities, Australia 2002*. Canberra, Australia: Australian Bureau of Statistics.

16. Australian Sports Commission. (1997). *Active Australia: a national participation framework*. Canberra, Australia: Australian Sports Commission.

17. Bauman, A. and Owen, N. (1999). Physical activity of adult Australians: epidemiological evidence and potential strategies for health gain. *Journal of Science and Medicine in Sport, 2*(1), 30-41.

18. Commonwealth Department of Health and Ageing. (1999). *National Physical Activity Guidelines for Australians*. Canberra, Australia: Commonwealth of Australia.

19. Finch, C., Ozanne-Smith, J. and Williams, F. (1995). *The feasibility of improved data collection methodologies for sports injuries*. Melbourne, Australia: Monash University Accident Research Centre.

20. Australian Government Department of Health and Ageing. (2004). *Sports safety in Australia: An update*. Canberra, Australia: Commonwealth of Australia.

21. Strategic Research Development Committee of the National Health and Medical Research Council. (1999). *Paradigm shift. Injury: from problem to solution. New research directions*. Canberra, Australia: Australian Government Publishing Service.

22. National Injury Prevention Advisory Council. (1999). *Directions in injury prevention. Report 1: Research needs*. Canberra: Commonwealth Department of Health and Aged Care.

23. Elliott, B. (2002). Biomechanics of injury: Its role in prevention, rehabilitation and orthopaedic outcomes. In Hong, Y. (Ed.), *International research in sports biomechanics*. London, UK: Routledge.

24. Elliott, B. (1999). Biomechanics: An integral part of sport science and sport medicine. *Journal of Science and Medicine in Sport, 2*(4), 299-310.

25. Winston, F.K., Schwarz, D.F. and Baker, S.P. (1996). Biomechanical epidemiology: a new approach to injury control research. *Journal of Trauma-Injury Infection and Critical Care, 40*(5), 820-824.

26. Finch, C., Valuri, G. and Ozanne-Smith, J. (1998). Sport and active recreation injuries in Australia: evidence from emergency department presentations. *British Journal of Sports Medicine, 32*(3), 220-225.

27. Cassell, E., Finch, C. and Stathakis, V. (2003). The epidemiology of medically-treated sport and active recreation injuries in the Latrobe Valley, Victoria. *British Journal of Sports Medicine, 37*, 405-409.

28. Cricket Australia. (2004). *National cricket census 2003-04*. Melbourne, Australia: Cricket Australia.

29. Orchard, J., James, T., Alcott, E., Carter, S. and Farhart, P. (2002). Injuries in Australian cricket at first class level 1995/1996 to 2000/2001. *British Journal of Sports Medicine, 36*(4), 270-274.

30. Gregory, P.L., Batt, M.E. and Wallace, W.A. (2002). Comparing injuries of spin bowling with fast bowling in young cricketers. *Clinical Journal of Sport Medicine, 12*(2), 107-112.

31. Stretch, R.A. (1993). The incidence and nature of injuries in first-league and provincial cricketers. *South African Medical Journal, 83*(5), 339-342.

32. Stretch, R.A. (1995). The seasonal incidence and nature of injuries in schoolboy cricketers. *South African Medical Journal, 85*(11), 1182-1184.

33. Stretch, R.A. (2001). Epidemiology of cricket injuries. *International Journal of Sports Medicine, 2*(2), 1-7.

34. Stretch, R.A. (2001). Incidence and nature of epidemiological injuries to elite South African cricket players. *South African Medical Journal, 91*(4), 336-339.

35. Stretch, R.A. (2003). Cricket injuries: a longitudinal study of the nature of injuries to South African cricketers. *British Journal of Sports Medicine, 37*(3), 250-253.

36. Orchard, J. and James, T. (2003). *Cricket Australia Injury Report 2003*. Melbourne, Australia: Cricket Australia.

37. Elliott, B.C., Foster, D.H. and Gray, S. (1986). Biomechanical and physical factors influencing fast bowling. *The Australian Journal of Science and Medicine in Sport, 18*(1), 16-21.

38. Elliott, B., Foster, D. and John, D. (1990). *The biomechanics of side-on and front-on fast bowling in cricket*. Nedlands, Australia: University of Western Australia.

39. Elliott, B.C. and Foster, D.H. (1984). A biomechanical analysis of the front-on and side-on fast bowling techniques. *Journal of Human Movement Studies, 10*(2), 83-94.

40. Elliott, B.C., Hardcastle, P.H., Burnett, A.F. and Foster, D.H. (1992). The influence of fast bowling and physical factors on radiologic features in high performance young fast bowlers. *Sports Medicine, Training and Rehabilitation, 3*(2), 113-130.

41. Foster, D. and John, D. (1987). *A study of junior fast bowlers - findings and recommendations: An interim report to The Australian Sports Commission and The Australian Cricket Board*. Nedlands, Australia: The University of Western Australia.

42. Foster, D., John, D., Elliott, B., Ackland, T. and Fitch, K. (1989). Back injuries to fast bowlers in cricket: A prospective study. *British Journal of Sports Medicine, 23*(3), 150-154.

43. Engstrom, C., Walker, D., Wallace, J., Hunter, J., Neal, R. and Kippers, V. (1995). *A combined morphometric and radiological assessment of the lumbar spines of elite fast bowlers from the Queensland Cricket Association: Morphometric aspects.* Paper presented at the The Australian Conference of Science and Medicine in Sport, Hobart, Australia.

44. Engstrom, C., Walker, D., Kippers, V., Hunter, J., Hanna, A. and Buckley, R. (1999). *A prospective study on back injury and muscle morphometry in junior cricket fast bowlers.* Paper presented at the 5th IOC World Congress on Sport Sciences with the Annual Conference of Science and Medicine in Sport, Sydney, Australia.

45. Mackay, G. and Keech, M. (1988). *Lumbosacral screening and prevention programme for junior elite male fast bowlers.* Paper presented at the 25th Anniversary Bicentennial Conference, The Australian Sports Medicine Federation Ltd, Sydney, Australia.

46. Dennis, R., Farhart, P., Clements, M. and Ledwidge, H. (2004). The relationship between fast bowling workload and injury in first-class cricketers: A pilot study. *Journal of Science and Medicine in Sport, 7*(2), 232-236.

47. Gregory, P.L., Batt, M.E. and Wallace, W.A. (2004). Is risk of fast bowling injury in cricketers greatest in those who bowl most? A cohort of young English fast bowlers. *British Journal of Sports Medicine, 38*(2), 125-128.

48. Finch, C.F., Elliott, B.C. and McGrath, A.C. (1999). Measures to prevent cricket injuries: An overview. *Sports Medicine, 28*(4), 263-272.

49. Bartlett, R.M. (2003). The science and medicine of cricket: An overview and update. *Journal of Sports Sciences, 21*(9), 733-752.

50. Author unknown.

51. Cricket Australia. (2004, 16 January). *Injury Report 2003* [press release]. Melbourne, Australia: Cricket Australia.

52. Kumar, S. (1999). *Chapter 1 - Selected theories of musculoskeletal injury causation*. London, UK: Taylor and Francis.

53. Finch, C.F. (1997). An overview of some definitional issues for sports injury surveillance. *Sports Medicine, 24*(3), 157-163.

54. Meeuwisse, W.H. (1994). Assessing causation in sport injury: A multifactorial model. *Clinical Journal of Sport Medicine, 4*, 166-170.

55. Kumar, S. (2001). Theories of musculoskeletal injury causation. *Ergonomics, 44*(1), 17-47.

56. Gregory, P.L. (2002). "Overuse" - an overused term? *British Journal of Sports Medicine, 36*(2), 82-83.

57. Elliott, B. (1999). Overuse injuries in sport: A biomechanical approach. *Safety Science Monitor, 3*, 1-6.

58. Burgess-Limerick, R. and Egeskov, R. (2004). Chapter 11: Risk factor identification - the role of ergonomics. In McClure, R., Stevenson, M. and McEvoy, S. (Eds.), *The scientific basis of injury prevention and control*. Melbourne, Australia: IP Communications.

59. Taunton, J.E., McKenzie, D.C. and Clement, D.B. (1988). The role of biomechanics in the epidemiology of injuries. *Sports Medicine, 6*(2), 107-120.

60. Whiting, W. and Zernicke, R. (1998). *Biomechanics of musculoskeletal injury*. Lower Mitcham, Australia: Human Kinetics.

61. DiFiori, J. (1999). Overuse injuries in children and adolescents. *The Physician and Sports Medicine, 27*(1), 75-89.

62. Fuller, C. and Drawer, S. (2004). The application of risk management in sport. *Sports Medicine, 34*(6), 349-356.

63. Connor, J. (2004). Chapter 9: Risk factor identification - the role of epidemiology. In McClure, R., Stevenson, M. and McEvoy, S. (Eds.), *The scientific basis of injury prevention and control*. Melbourne, Australia: IP Communications.

64. van Mechelen, W., Hlobil, H. and Kemper, H.C. (1992). Incidence, severity, aetiology and prevention of sports injuries. A review of concepts. *Sports Medicine, 14*(2), 82-99.

65. Meeuwisse, W.H. (1991). Predictability of sports injuries. What is the epidemiological evidence? *Sports Medicine, 12*(1), 8-15.

66. Bahr, R. and Holme, I. (2003). Risk factors for sports injuries - a methodological approach. *British Journal of Sports Medicine, 37*(5), 384-392.

67. Bahr, R. and Krosshaug, T. (2005). Understanding injury mechanisms: A key component of preventing injuries in sport. *British Journal of Sports Medicine, 39*(6), 324-329.

68. Finch, C. (2005). A new framework for research leading to sports injury prevention. *Journal of Science and Medicine in Sport, [in press]*.

69. Stevenson, M. and McClure, R. (2004). Introduction. In McClure, R., Stevenson, M. and McEvoy, S. (Eds.), *The scientific basis of injury prevention and control*. Melbourne, Australia: IP Communications.

70. Caine, C.G., Caine, D.J. and Lindner, K.L. (1996). Chapter 1. The epidemiologic approach to sports injuries. In *Epidemiology of sports injuries*. Champaign, USA: Human Kinetics.

71. McIntosh, A.S. (2005). Risk compensation, motivation, injuries, and biomechanics in competitive sport. *British Journal of Sports Medicine, 39*(1), 2-3.

72. McGill, S.M. (1997). The biomechanics of low back injury: Implications on current practice in industry and the clinic. *Journal of Biomechanics, 30*(5), 465-475.

73. Dalton, S.E. (1992). Overuse injuries in adolescent athletes. *Sports Medicine, 13*(1), 58-70.

74. Outerbridge, A.R. and Micheli, L.J. (1995). Overuse injuries in the young athlete. *Clinics in Sports Medicine, 14*(3), 503-516.

75. Krosshaug, T., Andersen, T.E., Olsen, O.E.O., Myklebust, G. and Bahr, R. (2005). Research approaches to describe the mechanisms of injuries in sport: Limitations and possibilities. *British Journal of Sports Medicine, 39*(6), 330-339.

76. Harvey, D. (1998). Assessment of the flexibility of elite athletes using the modified Thomas test. *British Journal of Sports Medicine, 32*(1), 68-70.

77. Harvey, D. (1998). *Screening test protocols. Pre-participation screening of athletes: A program developed by the Australian Institute of Sport, Olympic Athlete Program and the Australian Sports Injury Prevention Taskforce*. Canberra, Australia: Australian Sports Commission.

78. Gabbe, B.J., Bennell, K.L., Wajswelner, H. and Finch, C.F. (2004). Reliability of common lower extremity musculoskeletal screening tests. *Physical Therapy in Sport, 5*(2), 90-97.

79. Haas, M. (1995). How to evaluate intraexaminer reliability using an interexaminer reliability study design. *Journal of Manipulative and Physiological Therapeutics, 18*(1), 10-15.

80. Jekel, J.F., Katz, D.L. and Elmore, J.G. (2001). *Epidemiology, biostatistics and preventive medicine* (2nd ed.). Sydney, Australia: W.B. Saunders.

81. Walter, S.D., Sutton, J.R., McIntosh, J.M. and Connolly, C. (1985). The aetiology of sport injuries: A review of methodologies. *Sports Medicine, 2*, 47-58.

82. Grulich, A. (1998). Unit 18: Analytic studies - cohort and case-control studies. In Kerr, C., Taylor, R. and Heard, G. (Eds.), *Handbook of public health methods*. Sydney, Australia: McGraw Hill.

83. Yorkston, E., Arthur, C., Barker, T., Purdie, D. and McClure, R. (2005). Inflatable rescue boat-related injuries in Queensland surf lifesavers: The epidemiology - biomechanics interface. *International Journal of Injury Control and Safety Promotion, 12*(1), 39-44.

84. Sherker, S., Ozanne-Smith, J., Rechnitzer, G. and Grzebieta, R. (2003). Development of a multidisciplinary method to determine risk factors for

arm fracture in falls from playground equipment. *Injury Prevention, 9*(3), 279-283.

85. Weightman, D. and Browne, R.C. (1975). Injuries in eleven selected sports. *British Journal of Sports Medicine, 9*, 136-141.

86. Temple, R. (1982). Cricket injuries: Fast pitches change the gentleman's sport. *The Physician and Sportsmedicine, 10*(6), 186-192.

87. Orchard, J. and James, T. (2004). *Cricket Australia Injury Report 2004*. Melbourne, Australia: Cricket Australia.

88. Leary, T. and White, J.A. (2000). Acute injury incidence in professional county club cricket players (1985-1995). *British Journal of Sports Medicine, 34*(2), 145-147.

89. Orchard, J. (2003). *Orchard Sports Injury Classification System (OSICS): Version 8.2*. Retrieved 1 May, 2005, from http://www.injuryupdate.com.au/research/OSICS.htm

90. Orchard, J.W., Newman, D., Stretch, R., Frost, W., Mansingh, A. and Leipus, A. (2005). Methods for injury surveillance in international cricket. *British Journal of Sports Medicine, 39*(4), e22.

91. Elliott, B., Burnett, A. and Marshall, B. (1996). *The effect of fatigue on fast bowling technique in cricket: Summary report*. Nedlands, Australia: The University of Western Australia.

92. Elliott, B., Foster, D. and Blanksby, B. (1989). *Send the stumps flying: The science of fast bowling*. Nedlands, Australia: University of Western Australia Press.

93. Hurrion, P.D., Dyson, R. and Hale, T. (2000). Simultaneous measurement of back and front foot ground reaction forces during the same delivery

stride of the fast-medium bowler. *Journal of Sports Sciences, 18*(12), 993-997.

94. Mason, B.R., Weissensteiner, J.R. and Spence, P.R. (1989). Development of a model for fast bowling in cricket. *Excel, 6*(1), 3-12.

95. Elliott, B., Burnett, A., Stockhill, N. and Bartlett, R. (1995). The fast bowler in cricket: A sports medicine perspective. *Sports Exercise and Injury, 1*(4), 201-206.

96. Walker, D., Engstrom, C., Wallace, J. and Kippers, V. (1995). *A combined morphometric and radiological assessment of the lumbar spines of elite fast bowlers from the Queensland Cricket Association: Radiological aspects.* Paper presented at the The Australian Conference of Science and Medicine in Sport, Hobart, Australia.

97. Walker, D., Engstrom, C., Wallace, R. and Hunter, J. (1996). *Magnetic resonance imaging of the spine in junior cricket fast bowlers.* Paper presented at the The Australian Conference of Science and Medicine in Sport, Canberra, Australia.

98. Ranson, C.A., Kerslake, R.W., Burnett, A.F., Batt, M.E. and Abdi, S. (2005). Magnetic resonance imaging of the lumbar spine in asymptomatic professional fast bowlers in cricket. *Journal of Bone and Joint Surgery British, 87*(8), 1111-1116.

99. Stockhill, N.P. and Bartlett, R.M. (1992). *A three dimensional cinematographical analysis of the techniques of international and English county cricket fast bowlers.* Paper presented at the 10th Symposium of the International Society of Biomechanics in Sport, Milan, Italy.

100. Portus, M. (2001). *The relationships between cricket fast bowling technique, trunk injuries and ball release speed.* Paper presented at the International Society of Biomechanics, 18th Congress, Zurich, Switzerland.

101. Burnett, A.F., Elliott, B.C. and Marshall, R.N. (1995). The effect of a 12-over spell on fast bowling technique in cricket. *Journal of Sports Sciences, 13*(4), 329-341.

102. Burnett, A.F., Khangure, M.S., Elliott, B.C., Foster, D.H., Marshall, R.N. and Hardcastle, P.H. (1996). Thoracolumbar disc degeneration in young fast bowlers in cricket: A follow-up study. *Clinical Biomechanics, 11*(6), 305-310.

103. Elliott, B.C. (2000). Back injuries and the fast bowler in cricket. *Journal of Sports Sciences, 18*(12), 983-991.

104. Portus, M.R., Sinclair, P.J., Burke, S.T., Moore, D.J. and Farhart, P.J. (2000). Cricket fast bowling performance and technique and the influence of selected physical factors during an 8-over spell. *Journal of Sports Sciences, 18*(12), 999-1011.

105. Australian Cricket Board. (1998). *National Pace Bowling Program Resource Kit*. Melbourne, Australia: Australian Cricket Board.

106. Elliott, B. and Khangure, M. (2002). Disk degeneration and fast bowling in cricket: An intervention study. *Medicine and Science in Sports and Exercise, 34*(11), 1714-1718.

107. Stockhill, N.P. and Bartlett, R.M. (1993). *A temporal and kinematic comparison of junior and senior international cricket bowlers.* Paper

presented at the XIVth Congress of the International Society of Biomechanics, Paris, France.

108. Bell, P.A. (1992). Spondylolysis in fast bowlers: Principles of prevention and a survey of awareness among cricket coaches. *British Journal of Sports Medicine, 26*(4), 273-275.

109. Burnett, A., Elliott, B., Foster, D. and Hardcastle, P. (1991). The back breaks before the wicket: The young fast bowler's spine. *Sport Health, 9*(4), 11-15.

110. Gray, J., Derman, W. and Vaughan, C.L. (2000). Low back pain in cricket fast bowlers. *International Journal of Sports Medicine, 1*(4).

111. Annear, P.T., Chakera, T.M., Foster, D.H. and Hardcastle, P.H. (1992). Pars interarticularis stress and disc degeneration in cricket's potent strike force: The fast bowler. *Australian and New Zealand Journal of Surgery, 62*(10), 768-773.

112. Newell, T.M. and Kumar, S. (2005). Comparison of instantaneous and cumulative loads on the low back and neck in orthodontists. *Clinical Biomechanics, 20*(2), 130-137.

113. McIntosh, A. (2004). Chapter 10: Risk factor identification - the role of biomechanics. In McClure, R., Stevenson, M. and McEvoy, S. (Eds.), *The scientific basis of injury prevention and control*. Melbourne, Australia: IP Communications.

114. Waters, T.R., Putz-Anderson, V., Garg, A. and Fine, L.J. (1993). Revised NIOSH equation for the design and evaluation of manual lifting tasks. *Ergonomics, 36*(7), 749-776.

115. Purdam, C. (1989). Towards a better understanding of overuse injuries. *Excel, 5*(3), 7-11.

116. Bennell, K., Matheson, G., Meeuwisse, W. and Brukner, P. (1999). Risk factors for stress fractures. *Sports Medicine, 28*(2), 91-122.

117. Brukner, P. (1996). Sports medicine. Overuse injuries. Part I: Bone. *Australian Family Physician, 25*(4), 545-549.

118. Gobbi, A., Nunag, P. and Malinowski, K. (2005). Treatment of full thickness chondral lesions of the knee with microfracture in a group of athletes. *Knee Surgery, Sports Traumatology, Arthroscopy. 13*(3), 213-221.

119. Maganaris, C.N., Narici, M.V., Almekinders, L.C. and Maffulli, N. (2004). Biomechanics and pathophysiology of overuse tendon injuries: Ideas on insertional tendinopathy. *Sports Medicine, 34*(14), 1005-1017.

120. Woo, S., Apreleva, M. and Hoher, J. (1999). Chapter 2: Tissue mechanics of ligaments and tendons. In Kumar, S. (Ed.), *Biomechanics in ergonomics*. London, UK: Taylor and Francis.

121. Vad, V., Gebeh, A. and Dines, D. (2003). Hip and shoulder internal rotation range of motion deficits in professional tennis players. *Journal of Science and Medicine in Sport, 6*(1), 71-75.

122. Slavotinek, J.P., Verrall, G.M. and Fon, G.T. (2002). Hamstring injury in athletes: Using MR imaging measurements to compare extent of muscle injury with amount of time lost from competition. *American Journal of Roentgenology, 179*(6), 1621-1628.

123. Cross, T.M., Gibbs, N., Houang, M.T. and Cameron, M. (2004). Acute quadriceps muscle strains: Magnetic resonance imaging features and prognosis. *American Journal of Sports Medicine, 32*(3), 710-719.

124. Weishaupt, D., Schweitzer, M.E. and Morrison, W.B. (2001). Injuries to the distal gastrocnemius muscle: MR findings. *Journal of Computer Assisted Tomography, 25*(5), 677-682.

125. Tuite, D.J., Finegan, P.J., Saliaris, A.P., Renstrom, P.A., Donne, B. and O'Brien, M. (1998). Anatomy of the proximal musculotendinous junction of the adductor longus muscle. *Knee Surgery, Sports Traumatology, Arthroscopy. 6*(2), 134-137.

126. Guy, J.A. and Micheli, L.J. (1998). Stress injuries of the spine in young athletes. *Seminars in Spine Surgery, 10*(1), 81-87.

127. Maffulli, N. and Caine, D. (2005). The epidemiology of children's team sports injuries. *Medicine and Sport Science, 49*, 1-8.

128. d'Amato, C. (2005). Pediatric spinal trauma: Injuries in very young children. *Clinical Orthopaedics and Related Research, 432*, 34-40.

129. Gerrard, D.F. (1993). Overuse injury and growing bones: The young athlete at risk. *British Journal of Sports Medicine, 27*(1), 14-18.

130. Clark, P. and Letts, M. (2001). Trauma to the thoracic and lumbar spine in the adolescent. *Canadian Journal of Surgery, 44*(5), 337-345.

131. Nuckley, D.J., Eck, M.P., Carter, J.W. and Ching, R.P. (2004). Spinal maturation affects vertebral compressive mechanics and vBMD with sex dependence. *Bone, 35*(3), 720-728.

132. Bogduk, N. and Twomey, L. (1991). *Clinical anatomy of the lumbar spine* (2nd ed.). Melbourne, Australia: Churchill Livingstone.

133. Hadley, M.N., Zabramski, J.M., Browner, C.M., Rekate, H. and Sonntag, V.K. (1988). Pediatric spinal trauma. Review of 122 cases of spinal cord and vertebral column injuries. *Journal of Neurosurgery, 68*(1), 18-24.

134. Solomonow, M., Zhou, B.H., Baratta, R.V., Lu, Y. and Harris, M. (1999). Biomechanics of increased exposure to lumbar injury caused by cyclic loading: Part 1. Loss of reflexive muscular stabilization. *Spine, 24*(23), 2426-2434.

135. Chow, D.H., Luk, K.D., Leong, J.C. and Woo, C.W. (1989). Torsional stability of the lumbosacral junction. Significance of the iliolumbar ligament. *Spine, 14*(6), 611-615.

136. Pool-Goudzwaard, A., Hoek van Dijke, G., Mulder, P., Spoor, C., Snijders, C. and Stoeckart, R. (2003). The iliolumbar ligament: Its influence on stability of the sacroiliac joint. *Clinical Biomechanics, 18*(2), 99-105.

137. Luk, K.D., Ho, H.C. and Leong, J.C. (1986). The iliolumbar ligament. A study of its anatomy, development and clinical significance. *Journal of Bone and Joint Surgery British, 68*(2), 197-200.

138. d'Hemecourt, P.A., Micheli, L.J. and Gerbino, P. (2002). Spinal injuries in female athletes. *Sports Medicine and Arthroscopy Review, 10*, 91-97.

139. Palastanga, N., Field, D. and Soames, R. (1995). *Anatomy of human movement: Structure and function* (2nd ed.). Sydney, Australia: Butterworth Heinemann.

140. Warwick, R. and Williams, P.L. (Eds.). (1973). *Grays anatomy* (35th British ed.). Philadelphia, USA: W.B. Saunders.

141. Portus, M. (2001). *AIS biomechanics cricket fast bowling data 1996-1999: The relationships between technique, trunk injuries and ball release speed*. Canberra, Australia: Australian Institute of Sport.

142. de Loes, M. (1997). Exposure data. Why are they needed? *Sports Medicine, 24*(3), 172-175.

143. Foster, D. and John, D. (1987). *The inter-relationships between fast bowling techniques, physical characteristics and physiological capacities of junior fast bowlers, to injuries in cricket: an interim report to The Australian Sports Commission and The Australian Cricket Board*. Nedlands, Western Australia: The University of Western Australia.

144. Dennis, R. (2001). *The relationship between fast bowling workload and injury in first class male cricketers*. [Honours thesis]. School of Nursing, Family and Community Health; College of Social and Health Sciences. University of Western Sydney.

145. Foster, D., Elliott, B., Gray, S. and Herzberg, L. (1984). Guidelines for the fast bowler. *Sports Coach, 7*(4), 47-48.

146. Dupont, W.D. (2002). *Statistical modeling for biomedical researchers: A simple introduction to the analysis of complex data*. Melbourne, Australia: Cambridge University Press.

147. Cricket Australia. (2004). *Junior Cricket Policy*. Melbourne, Australia: Cricket Australia.

148. Dennis, R., Farhart, P., Goumas, C. and Orchard, J. (2003). Bowling workload and the risk of injury in elite cricket fast bowlers. *Journal of Science and Medicine in Sport, 6*(3), 359-367.

149. Saifuddin, A. and Burnett, S.J. (1997). The value of lumbar spine MRI in the assessment of the pars interarticularis. *Clinical Radiology, 52*(9), 666-671.

150. Cross, T.M., Smart, R.C. and Thomson, J.E. (2003). Exposure to diagnostic ionizing radiation in sports medicine: assessing and monitoring the risk. *Clinical Journal of Sport Medicine, 13*(3), 164-170.

151. Berryman Reese, N. and Bandy, W.D. (2002). *Joint range of motion and muscle length testing*. Sydney, Australia: W.B. Saunders Company.

152. Norkin, C.C. and White, D.J. (1985). *Measurement of joint motion: A guide to goniometry*. Philadelphia, USA: F.A. Davis Company.

153. Rolls, A. and George, K. (2004). The relationship between hamstring muscle injuries and hamstring muscle length in young elite footballers. *Physical Therapy in Sport, 5*(4), 179-187.

154. Schache, A.G., Blanch, P.D. and Murphy, A.T. (2000). Relation of anterior pelvic tilt during running to clinical and kinematic measures of hip extension. *British Journal of Sports Medicine, 34*(4), 279-283.

155. Neely, F.G. (1998). Biomechanical risk factors for exercise-related lower limb injuries. *Sports Medicine, 26*(6), 395-413.

156. Murphy, D.F., Connolly, D.A. and Beynnon, B.D. (2003). Risk factors for lower extremity injury: A review of the literature. *British Journal of Sports Medicine, 37*(1), 13-29.

157. Vad, V.B., Bhat, A.L., Basrai, D., Gebeh, A., Aspergren, D.D. and Andrews, J.R. (2004). Low back pain in professional golfers: The role of associated hip and low back range-of-motion deficits. *American Journal of Sports Medicine, 32*(2), 494-497.

158. Sahrmann, S. (2002). Chapter 4: Movement impairment syndromes of the hip. In *Diagnosis and Treatment of Movement Dysfunction*. St. Louis, USA: Mosby.

159. Corin, G., Strutton, P.H. and McGregor, A.H. (2005). Establishment of a protocol to test fatigue of the trunk muscles. *British Journal of Sports Medicine, 39*(10), 731-735.

160. Pool-Goudzwaard, A.L., Vleeming, A., Stoeckart, R., Snijders, C.J. and Mens, J.M.A. (1998). Insufficient lumbopelvic stability: A clinical, anatomical and biomechanical approach to 'a-specific' low back pain. *Manual Therapy, 3*(1), 12-20.

161. Grebing, B.R. and Coughlin, M.J. (2004). Evaluation of Morton's theory of second metatarsal hypertrophy. *Journal of Bone and Joint Surgery American, 86*(7), 1375-1386.

162. Cook, J.L., Khan, K.M. and Purdam, C.R. (2001). Conservative treatment of patellar tendinopathy. *Physical Therapy in Sport, 2*(2), 54-65.

163. Bennell, K. and Brukner, P. (2005). Preventing and managing stress fractures in athletes. *Physical Therapy in Sport, 6*(4), 171-180.

164. Bartlett, R. (1999). *Sports biomechanics: Reducing injury and improving performance*. London, UK: Routledge.

165. Ross, W.D. and Marfell-Jones, M.J. (1998). Chapter 6: Kinanthropometry. In Heyward, V.H. (Ed.), *Advanced fitness assessment and exercise prescription* (3rd ed.). Champaign, USA: Human Kinetics.

166. Bourdon, P., Savage, B. and Done, R. (2000). Chapter 15: Protocols for the physiological assessment of cricket players. In Gore, C.J. (Ed.), *Physiological tests for elite athletes*. Leeds, UK: Human Kinetics.

167. Norton, K., Marfell-Jones, M., Whittingham, N., Kerr, D., Carter, L., Saddington, K. and Gore, C. (2000). Chapter 5: Anthropometric assessment protocols. In Gore, C.J. (Ed.), *Physiological tests for elite athletes*. Leeds, UK: Human Kinetics.

168. Ellis, L., Gastin, P., Lawrence, S., Savage, B., Buckeridge, A., Stapff, A., Tumilty, D., Quinn, A., Woolford, S. and Young, W. (2000). Chapter 9: Protocols for the physiological assessment of team sport players. In Gore, C.J. (Ed.), *Physiological tests for elite athletes*. Leeds, UK: Human Kinetics.

169. The National Coaching Foundation. (1995). *Measuring performance: A guide to field based fitness testing*. Leeds, UK: The National Coaching Foundation.

170. Ross, W.D. and Marfell-Jones, M.J. (1998). Kinanthropometry. In Heyward, V.H. (Ed.), *Advanced fitness assessment and exercise prescription* (3rd ed., pp. 223-309). Champaign, USA: Human Kinetics.

171. Young, W., MacDonald, C., Heggen, T. and Fitzpatrick, J. (1997). An evaluation of the specificity, validity and reliability of jumping tests. *Journal of Sports Medicine and Physical Fitness, 37*(4), 240-245.

172. Mohr, M., Krustrup, P. and Bangsbo, J. (2003). Match performance of high-standard soccer players with special reference to development of fatigue. *Journal of Sports Sciences, 21*(7), 519-528.

173. Bangsbo, J. (1996). Yo-yo tests: Endurance Test, Intermittent Endurance Test and Intermittent Recovery Test [audiovisual material]. Copenhagen, Denmark.

174. Holmich, P., Holmich, L.R. and Bjerg, A.M. (2004). Clinical examination of athletes with groin pain: An intraobserver and interobserver reliability study. *British Journal of Sports Medicine, 38*(4), 446-451.

175. Scott, D.A., Bond, E.Q., Sisto, S.A. and Nadler, S.F. (2004). The intra- and interrater reliability of hip muscle strength assessments using a handheld versus a portable dynamometer anchoring station. *Archives of Physical Medicine and Rehabilitation, 85*(4), 598-603.

176. Click Fenter, P., Bellew, J.W., Pitts, T.A. and Kay, R.E. (2003). Reliability of stabilised commercial dynamometers for measuring hip abduction strength: A pilot study. *British Journal of Sports Medicine, 37*(4), 331-334.

177. McKenna, L., Cunningham, J. and Straker, L. (2004). Inter-tester reliability of scapular position in junior elite swimmers. *Physical Therapy in Sport, 5*(3), 146-155.

178. Maulder, P. and Cronin, J. (2005). Horizontal and vertical jump assessment: Reliability, symmetry, discriminative and predictive ability. *Physical Therapy in Sport, 6*(2), 74-82.

179. Stockbrugger, B.A. and Haennel, R.G. (2001). Validity and reliability of a medicine ball explosive power test. *Journal of Strength and Conditioning Research, 15*(4), 431-438.

180. Herrington, L.C. (2002). The inter-tester reliability of a clinical measurement used to determine the medial-lateral orientation of the patella. *Manual Therapy, 7*(3), 163-167.

181. Tousignant, M., Boucher, N., Bourbonnais, J., Gravelle, T., Quesnel, M. and Brosseau, L. (2001). Intratester and intertester reliability of the Cybex

electronic digital inclinometer (EDI-320) for measurement of active neck flexion and extension in healthy subjects. *Manual Therapy, 6*(4), 235-241.

182. Peolsson, A., Hedlund, R. and Oberg, B. (2001). Intra- and inter-tester reliability and reference values for hand strength. *Journal of Rehabilitation Medicine, 33*(1), 36-41.

183. Bennell, K.L., Talbot, R.C., Wajswelner, H., Techovanich, W., Kelly, D.H. and Hall, A.J. (1998). Intra-rater and inter-rater reliability of a weight-bearing lunge measure of ankle dorsiflexion. *Australian Journal of Physiotherapy, 44*(3), 175-180.

184. Clark, N.C., Gumbrell, C.J., Rana, S., Traole, C.M. and Morrissey, M.C. (2002). Intratester reliability and measurement error of the adapted crossover hop for distance. *Physical Therapy in Sport, 3*(3), 143-151.

185. Eliasziw, M., Young, S.L., Woodbury, M.G. and Fryday-Field, K. (1994). Statistical methodology for the concurrent assessment of interrater and intrarater reliability: Using goniometric measurements as an example. *Physical Therapy, 74*(8), 777-788.

186. Thomas, J.R. and Nelson, J.K. (1996). Measuring research variables. In *Research methods in physical activity* (3rd ed.). Champaign, USA: Human Kinetics.

187. Hopkins, W.G. (2000). Measures of reliability in sports medicine and science. *Sports Medicine, 30*(1), 1-15.

188. Batterham, A.M. and George, K.P. (2003). Reliability in evidence-based clinical practice: A primer for allied health professionals. *Physical Therapy in Sport, 4*(3), 122-128.

189. Downing, S.M. (2004). Reliability: On the reproducibility of assessment data. *Medical Education, 38*(9), 1006-1012.

190. Fleiss, J.L. (1986). Reliability of measurement. In Fleiss, J.L. (Ed.), *The design and analysis of clinical experiments*. New York: John Wiley & Sons.

191. Gajdosik, R.L. and Bohannon, R.W. (1987). Clinical measurement of range of motion. Review of goniometry emphasizing reliability and validity. *Physical Therapy, 67*(12), 1867-1872.

192. Shrout, P.E. and Fleiss, J.L. (1979). Intraclass correlations: Uses in assessing rater reliability. *Psychological Bulletin, 86*(2), 420-428.

193. Landis, J.R. and Koch, G.G. (1977). The measurement of observer agreement for categorical data. *Biometrics, 33*(1), 159-174.

194. Morrow Jr, J.R., Jackson, A.W., Disch, J.G. and Mood, D.P. (2005). *Measurement and evaluation in human performance* (3rd ed.). Champaign, USA: Human Kinetics.

195. Haas, M. (1991). The reliability of reliability. *Journal of Manipulative and Physiological Therapeutics, 14*(3), 199-208.

196. Elliott, B., Wallis, R., Sakurai, S., Lloyd, D. and Besier, T. (2002). The measurement of shoulder alignment in cricket fast bowling. *Journal of Sports Sciences, 20*(6), 507-510.

197. Krustrup, P., Mohr, M., Amstrup, T., Rysgaard, T., Johansen, J., Steensberg, A., Pedersen, P.K. and Bangsbo, J. (2003). The Yo-Yo intermittent recovery test: Physiological response, reliability, and validity. *Medicine and Science in Sports and Exercise, 35*(4), 697-705.

198. Wagner, D.R. and Heyward, V.H. (1999). Techniques of body composition assessment: A review of laboratory and field methods. *Research Quarterly for Exercise and Sport, 70*(2), 135-149.

199. McIntyre, M. (1991, November). Back injuries in cricket: Prevention is the key. *Between Overs,* 8-9.

200. Wallis, R., Elliott, B. and Koh, M. (2002). The effect of a fast bowling harness in cricket: An intervention study. *Journal of Sports Sciences, 20*(6), 495-506.

201. Stretch, R.A., Botha, T., Chandler, S. and Pretorius, P. (2003). Back injuries in young fast bowlers - a radiological investigation of the healing of spondylolysis and pedicle sclerosis. *South African Medical Journal, 93*(8), 611-616.

202. Millson, H.B., Gray, J., Stretch, R.A. and Lambert, M.I. (2004). Dissociation between back pain and bone stress reaction as measured by CT scan in young cricket fast bowlers. *British Journal of Sports Medicine, 38*(5), 586-591.

203. Connell, D.A., Jhamb, A. and James, T. (2003). Side strain: a tear of internal oblique musculature. *AJR. American Journal of Roentgenology, 181*(6), 1511-1517.

204. Solomonow, M., He Zhou, B., Baratta, R.V., Lu, Y., Zhu, M. and Harris, M. (2000). Biexponential recovery model of lumbar viscoelastic laxity and reflexive muscular activity after prolonged cyclic loading. *Clinical Biomechanics, 15*(3), 167-175.

205. Foster, C., Florhaug, J.A., Franklin, J., Gottschall, L., Hrovatin, L.A., Parker, S., Doleshal, P. and Dodge, C. (2001). A new approach to

monitoring exercise training. *Journal of Strength & Conditioning Research, 15*(1), 109-115.

206. Micheli, L.J. (1995). Sports injuries in children and adolescents. Questions and controversies. *Clinics in Sports Medicine, 14*(3), 727-745.

207. Lyman, S., Fleisig, G.S., Waterbor, J.W., Funkhouser, E.M., Pulley, L., Andrews, J.R., Osinski, E.D. and Roseman, J.M. (2001). Longitudinal study of elbow and shoulder pain in youth baseball pitchers. *Medicine and Science in Sports and Exercise, 33*(11), 1803-1810.

208. Lyman, S., Fleisig, G.S., Andrews, J.R. and Osinski, E.D. (2002). Effect of pitch type, pitch count, and pitching mechanics on risk of elbow and shoulder pain in youth baseball pitchers. *American Journal of Sports Medicine, 30*(4), 463-468.

209. Gabbe, B.J., Finch, C.F., Wajswelner, H. and Bennell, K.L. (2004). Predictors of lower extremity injuries at the community level of Australian football. *Clinical Journal of Sport Medicine, 14*(2), 56-63.

210. Lun, V., Meeuwisse, W.H., Stergiou, P. and Stefanyshyn, D. (2004). Relation between running injury and static lower limb alignment in recreational runners. *British Journal of Sports Medicine, 38*(5), 576-580.

211. Burne, S.G., Khan, K.M., Boudville, P.B., Mallet, R.J., Newman, P.M., Steinman, L.J. and Thornton, E. (2004). Risk factors associated with exertional medial tibial pain: A 12 month prospective clinical study. *British Journal of Sports Medicine, 38*(4), 441-445.

212. Yates, B. and White, S. (2004). The incidence and risk factors in the development of medial tibial stress syndrome among naval recruits. *American Journal of Sports Medicine, 32*(3), 772-780.

213. Tabrizi, P., McIntyre, W.M., Quesnel, M.B. and Howard, A.W. (2000). Limited dorsiflexion predisposes to injuries of the ankle in children. *Journal of Bone and Joint Surgery British, 82*(8), 1103-1106.

214. Hughes, L.Y. (1985). Biomechanical analysis of the foot and ankle for predisposition to developing stress fractures. *Journal of Orthopaedic and Sports Physical Therapy, 7*(3), 96-101.

215. Harvey, D. and Mansfield, C. (2000). Chapter 7: Measuring flexibility for performance and injury prevention. In Gore, C.J. (Ed.), *Physiological tests for elite athletes*. Leeds, UK: Human Kinetics.

216. Gross, M.T. (1995). Lower quarter screening for skeletal malalignment - suggestions for orthotics and shoewear. *Journal of Orthopaedic and Sports Physical Therapy, 21*(6), 389-405.

217. Powers, C.M. (2003). The influence of altered lower-extremity kinematics on patellofemoral joint dysfunction: A theoretical perspective. *Journal of Orthopaedic and Sports Physical Therapy, 33*(11), 639-646.

218. Nyland, J., Kuzemchek, S., Parks, M. and Caborn, D.N. (2004). Femoral anteversion influences vastus medialis and gluteus medius EMG amplitude: Composite hip abductor EMG amplitude ratios during isometric combined hip abduction-external rotation. *Journal of Electromyography and Kinesiology, 14*(2), 255-261.

219. Fuller, M., Saltau, C. and Brown, A. (2004, 16 January). *Australia may rotate bowlers*. Retrieved 29 April, 2005, from http://www.theage.com.au/articles/2004/01/15/1073877964911.html?one click=true

220. Brown, A. (2004, 16 January). *Rotation is the future for quicks: Bracken*. Retrieved 29 April, 2005, from http://www.smh.com.au/articles/2004/01/16/1073877976378.html?oneclick=true

221. BBC Sport. (2003, 24 October). *Lillee fears for pacemen*. Retrieved 1 July, 2005, from http://news.bbc.co.uk/sport2/hi/cricket/3209887.stm

PART G PUBLICATIONS AND PRESENTATIONS

Listed below are the publications and presentations related to the material presented in this thesis.

G1 Peer-reviewed papers

- Dennis, R., Farhart, P., Goumas, C. and Orchard, J. (2003). Bowling workload and the risk of injury in elite cricket fast bowlers. Journal of Science and Medicine in Sport, 6(3), 359-367. A copy of the paper is attached as Appendix 1.

- Dennis, R.J., Finch, C.F. and Farhart, P.J. (2005). Is bowling workload a risk factor for injury to Australian junior cricket fast bowlers? *British Journal of Sports Medicine, 39*(11), 843-846. A copy of the paper is attached as Appendix 2.

- Dennis, R.J., Hayen, A. and Finch, C.F. (2005). Determining the intra- and inter-observer reliability of screening tools used in sports injury research. *Journal of Science and Medicine in Sport,* (submitted – currently under review). A copy of the paper is attached as Appendix 3.

G2 Published abstracts

- Dennis, R., Farhart, P., Goumas, C., Orchard, J. (2002). Cricket fast bowling workload and injury study 2000-2001. *Journal of Science and Medicine in*

Sport, *5*(4), 80. (Awarded conference prize for Best Paper Injury Prevention and Health Promotion).

- Dennis, R., Farhart, P., Goumas, C., Orchard, J. (2003). Cricket fast bowling workload and injury study 2000-2002. *Conference Proceedings and Abstracts: 1st Asia-Pacific Injury Prevention Conference and 6th National Conference on Injury Prevention and Control*, p34. (Awarded Student Bursary for attendance at the conference to present this paper).

- Dennis, R., Farhart, P., Goumas, C., Orchard, J. (2003). Cricket fast bowling workload and injury study 2000-2002. *A collection of papers from the Second World Congress of Science and Medicine in Cricket*, p340 – 342.

- Dennis, R., Farhart, P., Goumas, C., Orchard, J. (2003). Fast bowling guidelines for junior cricketers – are they suitable? *Journal of Science and Medicine in Sport, 6*(4), 56.

- Dennis, R., Farhart, P., Goumas, C., Orchard, J. (2004). Bowling workload and the risk of injury in cricket fast bowlers. *7th World Conference on Injury Prevention and Safety Promotion: Abstracts*, p175-176.

G3 Invited conference presentations

- 3rd National Sports Injury Prevention Conference. Canberra, Australia, October 2003:

    - Symposium: *Preventing sports injury in adolescent athletes.*

- NSW Conference of Science and Medicine in Sport. Sydney, Australia, March 2004:
    - Oral presentation: *Preventing injury to cricket fast bowlers.*
- Victorian Conference of Science and Medicine in Sport. Melbourne, Australia, March 2004:
    - Oral presentation: *The Australian Cricket Board's National Pace Bowling Program.*

G4 Other conference presentations

- Australian Conference of Science and Medicine in Sport. Melbourne, Australia, October 2002:
    - Oral presentation: *National Workload and Injury Study 2000-2001*.
- 2nd World Congress of Science and Medicine in Cricket . Cape Town, South Africa, February 2003:
    - Oral presentation: *Australian Cricket Board National Fast Bowling Workload and Injury Study 2000-2002.*
- 6th National Conference on Injury Prevention and Control. Perth, Australia, March 2003:
    - Oral presentation: *National Workload and Injury Study 2000-2002.*

- 7th World Conference on Injury Prevention and Safety Promotion. Vienna, Austria, June 2004:
    - Poster presentation: *Bowling workload and the risk of injury in cricket fast bowlers.*

G5 Invited presentations at other forums

- Australian Cricket Board Sports Science and Medicine Forum. Brisbane, Australia, June 2002:
    - Oral presentation: *National Workload and Injury Study 2000-2002.*
- Cricket Australia Sports Science and Medicine Forum. Brisbane, Australia, April 2005:
    - Oral presentation: *Bowling workload as a risk factor for injury to fast bowlers.*
- Cricket Australia National Pace Bowling Program. Brisbane, Australia, April 2005:
    - Oral presentation: *Establishing a national tracking system for fast bowlers.*
- Cricket Australia Level 3 Coaching Course. Canberra, Australia, July 2005
    - Oral presentation: *Bowling workload as a risk factor for injury to fast bowlers.*

PART H APPENDICES

Appendix 1 Peer-reviewed publication related to Chapter B1

Dennis, R., Farhart, P., Goumas, C. and Orchard, J. (2003). Bowling workload and the risk of injury in elite cricket fast bowlers. *Journal of Science and Medicine in Sport, 6*(3), 359-367.

Bowling workload and the risk of injury in elite cricket fast bowlers

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Dennis, R, Farhart, Goumas, C & Orchard, J (2003). Bowling workload and the risk of injury in elite cricket fast bowlers. *Journal of Science and Medicine in Sport 6 (3): 359-367.*

This study examined the relationship between the bowling workload of first-class cricket fast bowlers and injury with the aim of identifying a workload threshold at which point the risk of injury increases. Ninety male fast bowlers (mean age 27 years, range 18 - 38 years) from six Australian state squads were observed for the 2000-2001 and/or 2001-2002 cricket seasons. Workload was quantified by examining fixture scorecards and conducting surveillance at training sessions. Injury data was obtained from the Cricket Australia's Injury Surveillance System. Compared to bowlers with an average of 3-3.99 days between bowling sessions, bowlers with an average of less than 2 days (risk ratio (RR)= 2.4, 95% confidence interval (CI) 1.6 to 3.5) or 5 or more days between sessions (RR= 1.8, 95% CI 1.1 to 2.9) were at a significantly increased risk of injury. Compared to those bowlers with an average of 123-188 deliveries per week, bowlers with an average of fewer than 123 deliveries per week (RR= 1.4, 95% CI 1.0 to 2.0) or more than 188 deliveries per week (RR= 1.4, 95% CI 0.9 to 1.6) may also be at an increased risk of injury. There appears to be a dual fast bowling workload threshold beyond which the risk of injury increases and maintaining a workload that is too low or infrequent is an equally significant risk factor for injury as maintaining a high bowling workload. Further study is required to determine the reason why players who bowl infrequently suffer more injuries.

Introduction

Cricket is a team sport for two teams of eleven players each. Although the game play and rules are very different, the basic concept of cricket is similar to that of baseball. Teams bat in successive innings and attempt to score runs, while the opposing team bowls (with fast and spin bowlers) and attempts to bring an end to the batting team's innings. After each team has batted an equal number of innings (either one or two, depending on the type of match), the team with the most runs wins[(1)].

Cricket is one of Australia's most popular sports, both in terms of participation rates and spectator interest. The Cricket Australia's Australian Cricket Census recorded 316,000 club cricketers and 179,000 school participants in 2001-02[(2)]. However it has been estimated from Australian Bureau of Statistics (ABS) population based surveys that 9-12% of Australians over the age of 16 participated in cricket, whether formally or informally, between 1987 and 1991[(3)]. The ABS has also rated cricket second to golf as the most popular participation sport for males and ninth for females[(3)]. As shown by these figures, cricket is a popular recreation activity as well as a formal sport.

Injury to elite first class cricketers is a considerable problem confronting administrators, sports medicine professionals and coaching staff. During the 2000-2001 season the overall injury match incidence was 20.4 injuries per 10,000 player hours[4]. The seasonal injury incidence for the same season was 17.2 injuries per team. Injury prevalence (percentage of players unavailable for selection for a match at any given time) was 14% of fast bowlers, 4% of spin bowlers and 4% of batsmen[4].

The incidence of injury, particularly to the lumbar vertebrae and associated tissues, has become of major concern to coaches, medical staff and players[8]. Previous research has been conducted in an attempt to determine the causes of injury to fast bowlers. These studies have found that there is no single cause, but rather a combination of factors that may predispose a bowler to injury[9,10,11]. It has been proposed that overuse (in terms of bowling volume), poor technique, poor physical preparation or a combination of these factors all play a role in predisposing a bowler to injury[10]. However, prior to the pilot study conducted with the New South Wales state squad in 1999-2000[5], no reported research had examined the relationship between the total bowling workload of fast bowlers and injuries sustained. By measuring the actual number of balls bowled by fast bowlers per week, per month and per season in both matches and training sessions, appropriate policies can be developed through investigation of the relationship between workload and the incidence of injury.

Similar research has been conducted with youth baseball players with an average age of 10.8 years which examined the relationship between pitch type and pitch volume with elbow and shoulder pain. This research found that the risk of elbow pain was increased for those throwing fewer than 300 pitches or more than 600 pitches during the season and the risk of shoulder pain increased when throwing more than 75 pitches per game and throwing fewer than 300 pitches during the season[6]. Another study found that youth pitchers with an average age of 12 years demonstrated an increased risk of elbow and shoulder pain with an increased number of pitches per game and with an increased number of pitches over the course of the season[7].

Therefore, it is hypothesised that through the examination of injury risk as a function of cricket fast bowling workload it will be possible to identify a threshold, which if exceeded, leads to a significant increase in the risk of injury.

Methods

Participants

Ninety male fast and fast-medium bowlers of mean age 27 years (range 18-38 years) were observed for the 2000-2001 and/or 2001-2002 Australian summer cricket seasons. Of this group, 51 participants were monitored during both seasons; 14 participants were monitored during the 2000-2001 season only and 25 participants were monitored during the 2001-2002 season only. These bowlers had all been selected in one of the six state cricket squads in Australia, ensuring the participants in this study were of a similar skill level. For the purposes of this project, a fast or fast-medium bowler has been defined as a bowler for whom the wicketkeeper would normally stand back from the stumps, due to the increased speed (and therefore distance travelled) of the ball when bowled.

Evaluating bowling workload

The methods of bowling workload data collection used in this study were adapted from those used in the pilot study[5]. Video surveillance of state squad training sessions was found to be an accurate method of evaluating bowling workload in the pilot study. However it was also determined to be expensive and time consuming if used in six locations as required in the present study. Therefore, bowling workload was determined in this study by employing research assistants to attend and observe each state squad training session.

Bowling workload has been evaluated by examining the frequency of bowling, the type of bowling performed (match or training) and by recording the time frame within which the bowling was completed. This was achieved by recording the number of bowling sessions and deliveries (match or training) bowled in a given period of time (i.e. workload per session, per week, per month and per season). To achieve the aim of quantifying total seasonal bowling workload, it was necessary to monitor the National Squad, State Squad and Grade training sessions in addition to any matches in which the participants participated throughout the season.

Bowling completed in Pura Cup, ING Cup, ACB Cup, Grade Competitions, Orange Test matches, VB One-Day matches, tour or promotional matches was categorised as match workload. Training workload included formal training sessions or personal training. Warm-up deliveries completed at the start of a match day were added to the deliveries bowled during the formal match situation and workload for this day was classified as match workload.

Research assistants were employed in each of the states to attend State Squad training sessions. When players were required to travel interstate, the research assistant employed in that state monitored training sessions. The scorer for the Australian team kept a record of national squad training deliveries for those bowlers who were selected in the Australian One Day and Test squads. It was expected that subjects would participate in a limited number of training sessions for their grade clubs throughout the season due to competing commitments to their state squad. Bowlers were asked to keep a record of the number of deliveries they bowled at grade team training sessions and provide this information to the research assistant attending the state squad training sessions. Bowling workload data were transferred to the study coordinator on a weekly basis and entered into a central database.

Bowling workload in matches was determined from the fixture scorecards. It is also usual practice for players to complete a warm-up session at the commencement of each match day. As in the pilot study, an estimate of 18 deliveries per bowler was recorded as the warm-up component for each match day played for the duration of the season[5].

Injury surveillance

Information pertaining to the incidence and nature of injuries sustained was obtained from the Injury Surveillance System implemented by the Cricket Australia and administered by sports medicine professionals for each of the State and Australian Squads[4]. This information was used to develop an overview of the injuries sustained throughout the season. An injury was defined as a condition that affects availability for team selection, limits performance during a major match or requires surgery[4]. Injuries were reported by the team doctor or the main team physiotherapist and information regarding the date of onset, diagnosis, mechanism and onset of injury was recorded. As outlined by Orchard and colleagues, injury diagnosis was coded in a cricket-specific modification of the OSICS system[4]. All injuries included in the present study were reported as having the mechanism of "gradual bowling"[4]. Therefore those injuries identified as having an acute onset or being collision-type injuries, such as slipping or colliding with another player, were not examined in this study.

Statistical procedures

Results were determined individually for the 2000-2001 season (65 bowlers) and the 2001-2002 season (76 bowlers). The datasets were also combined and pooled results have been reported for this dataset. Bowling workload has been described for all bowlers for the duration of each season; reported as 'entire season'. It has also been described for each of the bowlers prior to the occurrence of injury; reported as 'prior to injury'. Therefore, for those individual bowlers who did not sustain an injury, workload was the same for both categories.

To describe and evaluate the relationship between workload and injury, comparisons were made between injured and uninjured bowlers. For those bowlers who were injured, comparisons were also made between the session in which the injury occurred and all other sessions in which the player bowled throughout the season. Comparisons of the mean scores between groups were conducted using 2-sample independent t-tests in SAS. Paired t-tests were performed to compare the workload of injured bowlers between different time periods.

Whilst all injuries were recorded, if a player sustained multiple injuries or recurrences of an injury within a season, only the workload prior to the first major injury occurrence has been reported. As players may not bowl for a period of time following injury or may change bowling behaviour once an injury has been sustained, it was decided to restrict workload and injury analysis to the first major injury alone.

When calculating the average weekly workload of individual bowlers, only those weeks in which the player bowled were included. This was to ensure that the mean number of deliveries would not be influenced by periods of inactivity due to being injured or the fact that training sessions and matches were not scheduled (i.e. during the Christmas holiday period).

The risk of injury for a particular workload was assessed in this study. Injury risk is defined as the probability of an injury occurring in a group with a particular workload within a given period. Comparison of the risk of injury was made for workload variables that were defined as high and low workload (as determined by the mean or upper and lower quartiles). A risk ratio is defined as the ratio of risks within a given period of a group with a high bowling workload compared to a group with a low bowling workload. Risk ratios and confidence intervals were estimated using 2 x 2 frequency tables in SAS. The risk of injury for high and low workload groups were considered to be significantly different if the 95% confidence intervals of the risk ratio did not include 1.

To adjust for potential confounding of the relationship between workload and injury, risk of injury according to age group (in 5 year intervals) was conducted for each of the measures of workload (eg. days between bowling sessions, deliveries per week). Analyses examining the relationship between workload and injury were also conducted for match and training workload independently, in addition to total workload (match and training sessions combined).

Results

Injuries sustained

In the 2000-2001 and 2001-2002 seasons, respectively, 38 and 46 bowlers sustained a total of 57 and 67 injuries with a mechanism of "gradual bowling". Injuries sustained included muscular strains, tendon injuries, cartilage injuries, stress reactions and stress fractures. The epidemiology of injuries to Australian first-class cricketers, including the participants in the present study, is described by Orchard and colleagues[4].

Relationship between bowling workload and injury

The 90 participants yielded 9 044 observation sessions, with bowling exposure examined per day. The sessions were classified into match sessions (n= 5 382) and training sessions (n= 3 662). The relationship between total workload (match and training) and injury is reported below.

Frequency of sessions - days since previous session

Data from the two seasons were combined and the risk of injury for frequency of bowling sessions was determined using those players with an average frequency of 3-3.99 days between bowling sessions as the reference group. As shown in Table 1, those bowlers with an average of fewer than 2 days or 5 or more days between bowling sessions were at a significantly increased risk of injury.

When examining training workload independently, bowlers in 2000-2001 who on average had less than 6 days between training sessions were at 1.8 times the risk of sustaining injury as compared to those bowlers with 6 or more days between training sessions (95% CI 1.1-3.0). Similar results were obtained in 2001-2002, with bowlers with fewer than 6 days between training sessions being at 2 times the risk of injury (95% CI 1.5-2.7).

Average number of days between bowling sessions	Risk of injury as compared with bowlers with an average of 3 - 3.99 days between bowling sessions	95% confidence interval
< 2	2.4	1.6, 3.5
2 - 2.99	1.4	0.9, 2.2
3 - 3.99	1.0	
4 - 4.99	1.3	0.7, 2.3
≥ 5	1.8	1.1, 2.9

Table 1: Risk of injury for fast bowlers according to the average number of days between bowling sessions prior to injury (if any).

Season	Injured bowlers (A)	Uninjured bowlers (B)	A - B	p value (t-test) for A - B
1999-2000	235	165	70	<0.01
2000-2001	173	170	3	Not significant
2001-2002	160	142	22	<0.01

Table 2: The difference between the average number of deliveries bowled per week for injured and uninjured fast bowlers.

Deliveries per session

Comparisons showed that the mean number of total deliveries bowled on any given day in the 2001-2002 season for injured (mean= 59.2) and uninjured bowlers (mean= 58.9) did not differ significantly. However, when the combined data for two seasons were examined, it was found that those players who on average bowled fewer than 40 deliveries per session may be at an increased risk of injury (RR= 1.2, 95% CI 0.8-1.9) as compared with those bowlers who on average bowled more than 40 deliveries per session.

Deliveries per week

As shown in Table 2, a significant difference between injured and uninjured bowlers was seen in 2001-2002 in terms of the average number of deliveries bowled per week prior to any injury, which was consistent with the findings of the 1999-2000 pilot study[5].

A trend analysis was conducted on the combined data for the 2000-2001 and 2001-2002 seasons. Compared to those bowlers with an average of 123-188 deliveries per week, bowlers with an average of fewer than 123 deliveries per week (RR= 1.4, 95% CI 1.0 to 2.0) or more than 188 deliveries per week (RR= 1.4, 95% CI 0.9 to 1.6) may be at an increased risk of injury.

Age of bowlers

There was no appreciable difference in age between injured (mean= 25.9 years) and uninjured (mean= 25.4 years) bowlers (p=0.5). Age was divided into categories (15-19 years, 20-24 years, 25-29 years, 30-34 years, 35-39 years) and the risk of injury was compared between these age groups. There was some suggestion of an increased risk of injury for those aged 25-29 years (p=0.11). However, adjusting for age group for each of the measures of workload reported above did not appreciably affect the risk ratios in the defined workload groups.

Match versus training workload

To adjust for potential confounding of the relationship between workload and injury due to session type, match and training workload were analysed independently for their relationship with injury. The risk ratios in these analyses were similar to those obtained when examining total workload (match and training combined).

Discussion

The results of this study suggest that there is a dual workload threshold beyond which the risk of injury increases. A trend analysis conducted on the combined data for the 2000-2001 and 2001-2002 seasons for session frequency found that there are thresholds at both low and high frequency, beyond which risk of injury increases. These results suggest that bowling with an average of 2-5 days rest between bowling sessions has a protective effect and that those bowling less frequently than every 5 days or more frequently than every 2 days are at a significantly increased risk of injury. These findings generally suggest that allowing sufficient rest periods between bowling sessions is as important in preventing the occurrence of injury as monitoring the number of deliveries bowled, as was suggested in the pilot study[5]. Further study is required to determine why bowlers with a low bowling frequency appear more likely to be injured. A possible explanation is that there may be an ‘acquired resistance’ to injury which can be attained by bowling more frequently than once every five days. Hence this protective effect may be the result of exposure to an optimal level of loading. It is also possible that confounding factors may be responsible for this relationship (e.g. players with a past history of injury may be reluctant to bowl frequently).

To adjust for the potential confounding of session type, match and training workload were examined independently for their relationship with injury. The risk ratios obtained in these analyses were similar to those reported for total workload (match and training combined); therefore session type does not appear to confound or modify the association between total workload and injury. Whilst it was found that those bowling more frequently than every 2 days were at an increased risk of injury, when training sessions were examined independently, it was found that those bowling at training more frequently than every six days were at a significantly increased risk of injury. This is an important finding, as training workload is the most modifiable form of workload. It may be difficult to limit match workload (especially with professional players). However training workload is much easier to moderate.

Of the few studies that have examined weekly workload, only the number of bowling sessions or matches per week have been examined rather than the actual number of deliveries bowled. In the pilot study, weekly deliveries appeared to have a considerable role in the occurrence of injury, with injured bowlers bowling on average 70 deliveries more per week than uninjured bowlers(5). When the group was dichotomised into bowling above or below the mean, it was found that those bowlers bowling above 203 deliveries per week were 6 times more likely to sustain an injury. In the present study, there was not a significant difference in the weekly workload of uninjured and injured players. However, as with sessions frequency, a trend analysis on the combined data for the 2000-2001 and 2001-2002 seasons showed a dual threshold for injury, with those bowling fewer than 123 deliveries or more than 188 deliveries being at an increased risk of injury.

Whilst high workload has been identified as a possible risk factor for injury, it may also be possible that a certain workload is required to prevent injury and ensure the bowler is able to withstand the pressures of continued fast bowling. In the present study, it seems that maintaining a bowling workload that is too low or too infrequent is as significant a risk factor for injury as maintaining a high bowling workload. It may also be the case that certain types of injury are completely unrelated to workload. Through further examination of these possible risk factors as well as continued monitoring of workload, it may be possible to identify the role of each of these factors in the occurrence of certain types of injury. For example, workload may play a more significant role in some specific injuries but not others. As most injury categories do not have a frequency high enough to obtain a significant level of risk during the course of one season, this will only be possible once both injury and workload surveillance have been conducted over a number of seasons.

Although not examined in the present study it has been proposed that a mixed set-up at back foot impact and excessive counter-rotation in the delivery stride when bowling, poor physical condition and preparation, in addition to high bowling workload, may predispose a fast bowler to injury[9,11]. Other risk factors such as injury history, posture, anthropometric characteristics, footwear and playing surface may also play a role in the occurrence of injury. Risk factors for injury are either reversible or non-reversible and whilst past injury history cannot be changed, a risk factor such as bowling workload, especially training workload, may be changed. Whilst bowling workload was examined in detail, it is important to note that the technique and physical characteristics of the bowlers in the present study may have placed them at higher or lesser risk of injury. Further research needs to be conducted to investigate the relationship between technique and workload to assess whether technique changes as workload increases. There is also a need for further research to assess the effects of workload on physical characteristics such as muscle imbalances, posture and core stability deficiencies.

A limitation of previous research that has examined fast bowling workload is the absence of a definition and measure of bowling intensity. Examination of the frequency of match and training deliveries independently is the only manner in which intensity was considered in the present study. Obviously not all deliveries recorded throughout the season were bowled at full pace or with 100% effort. The only method currently available to measure bowling intensity is to examine bowling speed with a radar gun. However it is not practical to record the speed of each delivery bowled throughout the season. An alternative measure of intensity may be for bowlers to complete a diary that records the average percentage effort of each bowling session. However not only is this a subjective measure, but it is also likely to be misreported. A first class fast bowler vying for selection in the State or National team would rarely report that he or she had bowled with any less than 100% effort during a session.

Whilst continuing surveillance of first-class fast bowlers will allow the development of bowling workload guidelines for these players, such guidelines will be applicable only to first-class players and may bear little relevance to junior fast bowlers. Therefore, it would be necessary to conduct a similar study with junior cricketers to evaluate bowling workload as a risk factor for injury to young fast bowlers and develop appropriate guidelines. Also, as the focus of this study has been on the relationship fast bowling workload has with injury, future research may consider investigating the relationship between fast bowling workload and performance.

Conclusions

The results of this study suggest that to minimise the risk of injury, fast bowlers should bowl with a session frequency of 2-5 days, bowl in 2-3 sessions per week, bowl at training no more frequently than every 6 days and maintain an average of 123-188 deliveries per week throughout the season. As most state squads trained twice a week on average, perhaps bowlers could schedule a regular session on one day, with a lower workload during the second training session. Where possible, a sudden escalation in bowling workload should be avoided, especially if this increased workload is sustained. Whilst an increased workload during one bowling session does not place a bowler at an increased risk, it becomes a significant risk factor when a bowler continues this high workload over a longer period of time. A possible strategy to avoid this is to reduce training workload during periods of high match bowling workload. As workload is a reversible risk factor for injury (as compared to risk factors such as age and injury history), strategies for decreasing bowling workload should be considered by players, coaches, managers and administrative staff. Perhaps consideration can be given to the schedule of sessions in the week and month ahead and bowling workload in training sessions and matches modified accordingly.

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References

1. Mar D. *An explanation of cricket: Rules and game play described for novices*. Cited 20 September 2002 from URL http://www.aus.cricket.org/link_to_database/about_cricket/explanation/explanation_of_cricket.html#basics.

2. Cricket Australia. *Australian Cricket Census*. Cited 1 July 2003 from URL http://www.aus.cricket.org/link_to_database/national/aus/ca/development/census.html.

3. McGrath A, Finch C. *Bowling cricket injuries over: A review of the literature.* Melbourne. Monash University Accident Research Centre Report 105. 1996.

4. Orchard J, James T, Alcott E, et al. Injuries in Australian cricket at first class level 1995/1996 to 2000/2001. *British Journal of Sports Medicine 2002, 36,* 270-275.

5. Dennis R, Farhart P, Clements M, et al. The relationship between fast bowling workload and injury in first-class male cricketers: A pilot study. In press: Journal of Science and Medicine in Sport, 2003.

6. Lyman S, Fleisig G, Waterbor J, et al. Longitudinal study of elbow and shoulder pain in youth baseball pitchers. *Medicine and Science in Sports and Exercise 2001, 33* (11), 1803-1810.

7. Lyman S, Fleisig G, Andrews J, et al. Effect of pitch type, pitch count, and pitching mechanics on risk of elbow and shoulder pain in youth baseball pitchers. *American Journal of Sports Medicine 2002, 30* (4), 463-468.

8. Elliott B, Burnett A, Stockhill N, et al. The fast bowler in cricket: A sports medicine perspective. *Sports Exercise and Injury 1995, 1* (4), 201-206.

9. Foster D, John D, Elliott B, et al. Back injuries to fast bowlers in cricket: A prospective study. *British Journal of Sports Medicine 1989, 23* (3), 150-154.

10. Burnett A, Elliott B, Foster D, et al. The back breaks before the wicket: The young fast bowler's spine. *Sport Health 1991, 9* (4), 11-15.

11. Elliott B, Hardcastle P, Burnett A, et al. The influence of fast bowling and physical factors on radiologic features in high performance young fast bowlers. *Sports Medicine, Training and Rehabilitation 1992, 3* (2), 113-130.

Rebecca Dennis was the winner of the inaugural ASICS Best Paper - Injury Prevention and Health Promotion prize, offered by the Journal at the 2003 Australian Conference of Science and Medicine in Sport.

Appendix 2 Peer-reviewed publication related to Chapter B2

Dennis, R.J., Finch, C.F. and Farhart, P.J. (2005). Is bowling workload a risk factor for injury to Australian junior cricket fast bowlers? *British Journal of Sports Medicine, 39*(11), 843-846.

ORIGINAL ARTICLE

Is bowling workload a risk factor for injury to Australian junior cricket fast bowlers?

R J Dennis, C F Finch, P J Farhart

Br J Sports Med 2005;**39**:843–846. doi: 10.1136/bjsm.2005.018515

Objectives: To examine whether bowling workload is a risk factor for overuse injury to Australian junior cricket fast bowlers and to evaluate the appropriateness of current bowling workload guidelines.
Methods: Forty four male fast bowlers (mean (standard deviation) age 14.7 (1.4) years) were monitored prospectively over the 2002–2003 season. Bowlers completed a daily diary to record bowling workloads and self reported injuries, which were validated by a physiotherapist. Bowling workload prior to the first injury (for those bowlers who were injured) was compared to workload across the whole season for uninjured bowlers.
Results: Eleven (25%) bowlers reported an overuse-type injury, with seven of these sustaining a back injury. Injured bowlers had been bowling significantly more frequently than uninjured bowlers (median number of days since the previous bowling day: 3.2 *v* 3.9 days, Mann-Whitney U = 105.0, p = 0.038). Compared with bowlers with an average of ⩾3.5 rest days between bowling, bowlers with an average of <3.5 rest days were at a significantly increased risk of injury (risk ratio (RR) = 3.1, 95% confidence interval (CI) 1.1 to 8.9). There were also trends towards an increased risk of injury for those who bowled an average of ⩾2.5 days per week (RR = 2.5, 95% CI 0.9 to 7.4) or ⩾50 deliveries per day (RR = 2.0, 95% CI 0.7 to 5.4).
Conclusions: This study has identified high bowling workload as a risk factor for overuse injury to junior fast bowlers. Continued research is required to provide scientific evidence for bowling workload guidelines that are age-specific for junior fast bowlers.

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Cricket is one of Australia's most popular sports, with a total of 410 919 participants in organised programs in the 2003–2004 season, of whom approximately 70% were aged under 18 years.[1] Unfortunately, participation is associated with a risk of injury and a number of studies have documented the incidence of injury amongst both junior and senior players.[2–8] Fast bowlers have consistently been identified as being at the greatest risk of injury, with a combination of predisposing factors including poor technique, poor physical preparation, and overuse.[7 9–11] Indeed, overuse has been identified as a major contributing factor to the occurrence of injury, particularly amongst young fast bowlers.[4 7]

Overuse injuries are generally the result of repetitive microtrauma where a number of forces, each lower than the critical limit of the specific tissue, combine to produce a fatigue effect over time.[12] The developing musculoskeletal system is particularly vulnerable to overuse, with sites of vigorous development in long bones and musculotendinous attachments being areas of potential injury.[13 14] Participants in a number of activities, particularly those which require repetitive hyperextension of the lumbar spine (such as fast bowling), may experience low back pain as rapid growth of the vertebral bodies is not matched by that of the dorsal soft tissues.[13] The increased elasticity of the intervertebral disc, which may allow a greater proportion of torsional forces to reach the vertebrae,[15] incomplete ossification of the posterior vertebral elements until about 25 years of age,[16] and incomplete formation of the iliolumbar ligament (which may be a very important stabiliser of the lumbosacral junction) until the third decade of life[17 18] can each increase the propensity of junior athletes to injury. The most serious overuse injuries for young fast bowlers are those to the pars interarticularis, as they can potentially limit participation in the game for extended periods.[9 11 19]

While most previous aetiological research with fast bowlers has focused on biomechanical analyses of technique, few studies have examined bowling workload as an injury risk factor. Our study of Australian first class fast bowlers (mean age 27 years) found that bowling workload was highly associated with overuse injury,[20] as did a study with Australian junior fast bowlers.[9] In contrast, injury incidence was not higher in those that bowled the most in a cohort of young English fast bowlers.[21]

The Australian *Junior Cricket Policy* outlines bowling workload guidelines for junior fast bowlers, describing the maximum number of deliveries to be bowled in matches and training sessions for players aged <19 years.[22] The findings of our research conducted with senior fast bowlers[20] raised concerns about the appropriateness of the junior fast bowling workload guidelines, which are based on current best practice. In some cases, junior bowlers are permitted to bowl more than research has suggested is appropriate for senior fast bowlers (table 1).[20] In response to this disparity, Cricket Australia commissioned this study with junior fast bowlers. Thus, the aim of this study was to investigate bowling workload as a risk factor for injury to junior fast bowlers and evaluate the appropriateness of current bowling workload guidelines.

METHODS

Forty four male fast bowlers participating in club and district cricket with a mean (standard deviation) age of 14.7 (1.4) years (range 12–17 years) were prospectively monitored over the 2002–2003 Australian summer cricket season. A fast bowler was defined as a bowler for whom the wicketkeeper

Abbreviations: CI, confidence interval; MRI, magnetic resonance imaging; RR, risk ratio

Table 1 Current workload guidelines for junior fast bowlers and recommendations from research with first class fast bowlers

Age group (years)	Number of deliveries per match innings	Number of training sessions per week	Number of deliveries per training session	Maximum sessions per week	Maximum deliveries per week
Under 13	48	2	30	3	108
Under 15	60	2	36	3	132
Under 17	96	3	36	4	204
Under 19	120	3	42	4	246
First class*	N/A	1	40	3	188

*Findings from research conducted with fast bowlers with a mean age of 27 years.[20] All other data are from Cricket Australia's *Junior Cricket Policy.*[22]

would normally stand back from the stumps, due to the increased speed of the ball when bowled.[20 23]

Bowlers participating in this study were part of a larger prospective cohort study with both junior and senior fast bowlers undergoing a range of tests. The sample size for the larger cohort study (from which the junior participants were recruited for this bowling workload study) was largely determined by the resources required to complete the comprehensive testing protocols. All participants and their parents/guardians gave written, informed consent. Ethics approval was obtained from the Australian Institute of Sport.

Participants completed detailed logbooks, recording the number of match and training deliveries bowled each day for the duration of the 6 month season. This diary was forwarded on a weekly basis and entered into a central database. Bowling completed in organised 1 or 2 day matches was categorised as match workload. Training workload included formal training and informal personal training.

The definition of injury was adapted from that previously used.[2 20] An injury was defined as a condition that affected availability for team selection, limited performance during a match, or required surgery. Minor injuries which only affected participation in training sessions were not examined in this study. Injuries included in the analysis were overuse-type injuries as a result of bowling.[20] Therefore, all injuries had an insidious onset caused by repetitive episodes of microtrauma, rather than collision-type injuries. Bowlers were asked to report any condition or injury in their logbooks, even if unrelated to cricket. The bowlers were then contacted by a sports physiotherapist and each case was reviewed to determine if the injury met the inclusion criteria. As part of the larger cohort study, all bowlers underwent a magnetic resonance imaging (MRI) scan at the start of the season and immediately after any back/trunk injury. The results of the post-injury scan were used by the sports physiotherapist to confirm the injury diagnosis for this study. While MRI may not be the most sensitive radiological modality for diagnosis of lumbar bone stress injury,[24] it was chosen because of the issues of radiation exposure for adolescents associated with CT scan or bone scan.[25]

To evaluate the relationship between workload and injury, comparisons were made between injured and uninjured bowlers.[20] For those that were injured, only workload prior to the occurrence of injury was examined. For those that remained uninjured, workload for the entire season was reported. While all injuries were recorded, if a bowler sustained multiple injuries or recurrences of an injury during the season, only workload prior to the first injury is reported in this paper.

Data analysis was undertaken with SPSS (Chicago, IL, USA). Independent *t* tests and Mann-Whitney U tests (a distribution-free test which rank-orders data) were used for parametric and non-parametric data, respectively. The risk of injury for particular workloads was assessed by risk ratios (RR) and associated 95% confidence intervals (95% CI) as estimated from 2×2 tables. Risk ratios were considered to be significantly different if the 95% CI excluded the value 1.0.

RESULTS

The 44 players bowled on a total of 1783 bowling days, of which 39% were match days and 61% were training days. They bowled on an average of 1 match day and 1.5 training days per week, with an average of 55 and 36 deliveries per match and training day, respectively.

Eleven of the 44 bowlers (25%) reported a bowling related overuse injury during the season. Six of these injuries occurred in the first half of the season and the remaining five occurred in the second half of the season. Seven of the injured bowlers sustained a back injury (one bilateral stress fracture to the pars interarticularis, three stress reactions to the pars interarticularis contralateral to the bowling arm, one stress reaction to the pars interarticularis on the bowling side, and two lumbar musculoligamentous strains). Other injuries recorded were muscular strains to the shoulder and quadriceps, and calcaneal apophysitis. While not meeting the injury inclusion criteria, it is worth noting that 23 of the 44 bowlers (52%) reported back pain at some stage during the season. There was no difference in the mean age of the injured and uninjured bowlers (14.8 and 14.7 years, respectively).

Bowling workloads were examined to determine if the players had been exceeding the Cricket Australia *Junior Cricket Policy* guidelines (table 1).[22] Bowlers had exceeded the guidelines for the number of match deliveries to be bowled per day on only 8% of the match days. However, they exceeded the guidelines for the number of training deliveries to be bowled per day on 42% of the training days (median: 12 deliveries in excess of guidelines, range: 1–264 deliveries).

In comparing workloads, injured players bowled significantly more frequently, with the median number of days since the previous bowling day lower in injured bowlers compared with uninjured bowlers (median: 3.2 *v* 3.9 days, M rank: 171.0 and 819.0, respectively, Mann-Whitney $U = 105.0$, $p = 0.038$). There was a trend towards an increased injury risk for those bowlers with a high mean bowling workload, as measured by frequency of bowling days, days per week, and deliveries per day (table 2). There was no association found between the average number of deliveries bowled per week and injury.

DISCUSSION

This study is the first to examine the actual number of deliveries bowled by junior fast bowlers over the course of an entire cricket season. The importance of this sort of information to inform the development of evidence based guidelines for junior cricket programs has been recognised by the NSW Sporting Injuries Committee and Cricket Australia, who jointly funded this study.

Overall, the results suggest there is a relationship between high bowling workload and injury. As with first class fast bowlers,[20] increased bowling frequency is significantly associated with increased injury risk. Parents and coaches should be aware that programs designed for senior fast bowlers are not appropriate for junior players, who may be more prone to overuse injury because their bones and

Table 2 The risk of injury in junior fast bowlers according to mean bowling workload and the percentage of injured and uninjured bowlers with a high bowling workload

Mean bowling workload	% of injured bowlers with this workload (n = 11)	% of uninjured bowlers with this workload (n = 33)	Risk of injury as compared with bowlers with a lesser workload	95% CI
<3.5 days rest between bowling	64%	27%	3.1	1.1 to 8.9
⩾2.5 days per week	64%	33%	2.5	0.9 to 7.4
⩾50 deliveries per day	45%	24%	2.0	0.7 to 5.4
⩾100 deliveries per week	45%	39%	1.2	0.4 to 3.4

ligaments are not fully developed.[9 11 15–18 26] It is, therefore, important that workload guidelines are specific to junior players, as direct extrapolation from senior fast bowlers may not be appropriate due to these physical, growth related factors.

As shown in table 1, the recommended workloads for junior players in some cases exceed what has been suggested as being appropriate for much older players. It was not possible to stratify the analysis according to age group because of the small sample size and this study is therefore limited in its ability to propose changes in the guidelines for specific age groups. However, given the importance of bowling frequency, it does seem that rest days should be added to the guidelines. The results indicated that bowling more frequently than every 3.5 days (on average during the season) significantly increased injury risk. Bowlers also need to consider the amount of bowling completed during training or informal practise sessions. While the bowlers adhered to the match workload guidelines listed in the *Junior Cricket Policy*[22] (which are enforced by umpires), on 42% of training days they exceeded the recommended number of deliveries. As with baseball, match guidelines can be enforced, but there is the potential for dramatically increased numbers of deliveries in an informal setting.[27]

Fewer junior fast bowlers sustained a bowling related overuse injury than has been reported using the same methodology for senior fast bowlers (25% *v* 59%, respectively).[20] The rate of injury is also less than the 47% reported for South African schoolboy cricketers.[6] However, the comparability of these findings is limited, as the South African study reported injuries to bowlers in general and it is not clear what proportion of this group were fast bowlers. Furthermore, a more inclusive definition of injury was used. In a study of 70 young English fast bowlers, an injury rate of 32.8 per 100 bowlers was reported.[21] Although the definition of injury used was similar to ours, the analysis was not restricted to overuse-type injuries.[21]

Back injuries have been the focus of most previous research, as they can potentially limit participation in the game for extended periods.[9 11 19] Foster *et al* reported that 38% of the 82 Australian fast bowlers in their study sustained a back injury.[9] In the English junior fast bowlers study, 10% of bowlers reported back pain during the study period and one bowler sustained a stress fracture.[21] The frequency of bowlers reporting back pain (52%) and back injury (16%) in our study differed from the results of this previous research. As our definition of injury was comparable to the definitions in these two studies,[9 21] the dissimilarity in findings could be a result of differing bowling techniques, physical characteristics, or workloads of the participants. Foster *et al* found that both bowling technique and high workload were associated with injury, with 59% of the participants who bowled more than the mean number of matches for the group suffering a back injury, as compared with the overall back injury frequency of 38%.[9] In comparison, the English study found there was no increased injury risk in those that bowled the most.[21] However, in both prior studies, it appears that bowlers were compared according to the total number of sessions/deliveries bowled during the entire 6 month study period, which may include bowling completed after injury. We restricted our analysis to include bowling completed prior to injury (if any), due to the importance of distinguishing between injury risk factors and injury sequelae.[28] Also, as exposure was clearly established before injury, any potential bias associated with recall of risk exposure and injury history was eliminated.[29] The fact there was no difference between the workloads of injured and uninjured English fast bowlers may simply be because the injured bowlers could not bowl for a significant period of time after injury.

Another factor limiting direct comparison of the results with the English junior study, is that the latter examined workload and injury in 3 months of preseason training and the first 3 months of the season, while we monitored the 6 month cricket season.[21] As was noted by the authors of the English study,[21] injuries can become manifest after the study period, which in their case was the second half of the season. In our study, five of the 11 injuries occurred during that period. Therefore, it is possible that the English study found no relationship between injury risk and bowling workload because injuries may have occurred in the second half of the season, by which time the opportunity to bowl in matches (and bowling workload) would have increased greatly. However, it is also acknowledged that unless bowlers are monitored all year, or for subsequent seasons, injuries may become manifest after any selected study period.

While this study has the potential to contribute important information, we also recognise its limitations. The intensity of bowling was not considered in this study and it is acknowledged that not all deliveries recorded during the season would have been bowled at full pace. However, it is not practical to record the speed of every delivery bowled throughout the season with a radar gun and a self reported measure of bowling intensity is subjective and may be misreported.[20] Furthermore, to allow comparison with the existing bowling workload guidelines, bowling workload was only measured in terms of days bowled, rather than the actual duration of bowling spells and time between spells. Future research could consider rest periods and optimal fast bowling work to rest schedules in greater detail.

The small sample size resulted in a lack of power to detect small to moderate differences in the bowling workload of injured and uninjured bowlers and prevented the conduct of multivariate analysis. Continued research with a larger sample will allow multiple measures to be examined as possible injury risk factors and will also allow trend analysis for injury risk according to stratified bowling workloads. This may provide more detailed information about the possible injury risk with under-bowling and over-bowling, as has been provided with senior fast bowlers.[20] It may also be possible that similar risk factors will need to be weighted differently across different age groups because of the anatomical and physiological differences between adolescents and adults.

What is already known on this topic

Fast bowlers have consistently been identified as the cricket players at the greatest risk of injury, with a combination of predisposing factors including poor technique, poor physical preparation, and overuse. Previous research has reported that bowling workload is a significant risk factor for overuse injury to first class fast bowlers.

What this study adds

High bowling workload has been identified as a risk factor for overuse injury to junior fast bowlers. As with first class fast bowlers, increased bowling frequency is significantly associated with increased injury risk. Rest days should be considered for inclusion in bowling workload guidelines.

Future research may be able to determine if high bowling workload is a more potent risk factor for injury to junior fast bowlers as compared with senior fast bowlers.

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Ethics approval: written consent was provided by both the participants and their parents/guardians. The Australian Institute of Sport Ethics Committee provided approval for this project (c/o Australian Sports Commission, PO Box 176, Belconnen ACT 2616, Australia)

REFERENCES

1 **Cricket Australia**. *National cricket census 2003–04*. Melbourne, Australia: Cricket Australia, 2004.
2 **Orchard J**, James T, Alcott E, *et al*. Injuries in Australian cricket at first class level 1995/1996 to 2000/2001. *Br J Sports Med* 2002;**36**(4):270–4.
3 **Finch C**, Valuri G, Ozanne-Smith J. Sport and active recreation injuries in Australia: evidence from emergency department presentations. *Br J Sports Med* 1998;**32**(3):220–5.
4 **Stretch RA**. Cricket injuries: a longitudinal study of the nature of injuries to South African cricketers. *Br J Sports Med* 2003;**37**(3):250–3.
5 **Leary T**, White JA. Acute injury incidence in professional county club cricket players (1985–1995). *Br J Sports Med* 2000;**34**(2):145–7.
6 **Stretch RA**. The seasonal incidence and nature of injuries in schoolboy cricketers. *S Afr Med J* 1995;**85**(11):1182–4.
7 **Stretch RA**. The incidence and nature of injuries in first-league and provincial cricketers. *S Afr Med J* 1993;**83**(5):339–42.
8 **Gregory PL**, Batt ME, Wallace WA. Comparing injuries of spin bowling with fast bowling in young cricketers. *Clin J Sport Med* 2002;**12**(2):107–12.
9 **Foster D**, John D, Elliott B, *et al*. Back injuries to fast bowlers in cricket: a prospective study. *Br J Sports Med* 1989;**23**(3):150–4.
10 **Burnett A**, Elliott B, Foster D, *et al*. The back breaks before the wicket: the young fast bowler's spine. *Sport Health* 1991;**9**(4):11–15.
11 **Elliott BC**, Hardcastle PH, Burnett AF, *et al*. The influence of fast bowling and physical factors on radiologic features in high performance young fast bowlers. *Sports Med Training Rehabil* 1992;**3**(2):113–30.
12 **Elliott B**. Overuse injuries in sport: a biomechanical approach. *Saf Sci Monit* 1999;**3**:1–6.
13 **Gerrard DF**. Overuse injury and growing bones: the young athlete at risk. *Br J Sports Med* 1993;**27**(1):14–18.
14 **DiFiori J**. Overuse injuries in children and adolescents. *Physician Sports Med* 1999;**27**(1):75–89.
15 **Hadley MN**, Zabramski JM, Browner CM, *et al*. Pediatric spinal trauma. Review of 122 cases of spinal cord and vertebral column injuries. *J Neurosurg* 1988;**68**(1):18–24.
16 **Warwick R**, Williams PL, eds. *Gray's anatomy*, 35th British ed. Philadelphia: WB Saunders, 1973.
17 **Chow DH**, Luk KD, Leong JC, *et al*. Torsional stability of the lumbosacral junction. Significance of the iliolumbar ligament. *Spine* 1989;**14**(6):611–5.
18 **Luk KD**, Ho HC, Leong JC. The iliolumbar ligament. A study of its anatomy, development and clinical significance. *J Bone Joint Surg Br* 1986;**68**(2):197–200.
19 **Annear PT**, Chakera TM, Foster DH, *et al*. Pars interarticularis stress and disc degeneration in cricket's potent strike force: the fast bowler. *Aust N Z J Surg* 1992;**62**(10):768–73.
20 **Dennis R**, Farhart P, Goumas C, *et al*. Bowling workload and the risk of injury in elite cricket fast bowlers. *J Sci Med Sport* 2003;**6**(3):359–67.
21 **Gregory PL**, Batt ME, Wallace WA. Is risk of fast bowling injury in cricketers greatest in those who bowl most? A cohort of young English fast bowlers. *Br J Sports Med* 2004;**38**(2):125–8.
22 **Cricket Australia**. *Junior cricket policy*. Melbourne, Australia: Cricket Australia, April, 2004.
23 **Dennis R**, Farhart P, Clements M, *et al*. The relationship between fast bowling workload and injury in first-class cricketers: a pilot study. *J Sci Med Sport* 2004;**7**(2):232–6.
24 **Saifuddin A**, Burnett SJ. The value of lumbar spine MRI in the assessment of the pars interarticularis. *Clin Radiol* 1997;**52**(9):666–71.
25 **Cross TM**, Smart RC, Thomson JE. Exposure to diagnostic ionizing radiation in sports medicine: assessing and monitoring the risk. *Clin J Sports Med* 2003;**13**(3):164–70.
26 **Elliott B**, Burnett A, Stockhill N, *et al*. The fast bowler in cricket: a sports medicine perspective. *Sports Exerc Inj* 1995;**1**(4):201–6.
27 **Micheli LJ**. Sports injuries in children and adolescents. Questions and controversies. *Clin Sports Med* 1995;**14**(3):727–45.
28 **Bahr R**, Holme I. Risk factors for sports injuries - a methodological approach. *Br J Sports Med* 2003;**37**(5):384–92.
29 **Walter SD**, Sutton JR, McIntosh JM, *et al*. The aetiology of sport injuries: a review of methodologies. *Sports Med* 1985;**2**:47–58.

COMMENTARIES

Cricket is a popular team sport on the world stage, yet there have been relatively few publications in the medical literature regarding cricket injuries. Identifying risk factors for injury is an important component of any scientific research that aims to reduce injury incidence in sport. It cannot be assumed that research findings in the adult population can be applied to the teenage/young adult population. For these reasons this is a particularly worthwhile study that has identified bowling workload as a risk factor for overuse injury in junior fast bowlers. As the authors state, further research into various parameters of workload is required to provide more specific guidelines regarding volume, frequency, and age specificity.

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Bowling workloads have been identified as a major risk factor associated with injury in young fast bowlers around the world. As a result most major cricket playing countries have introduced some form of restriction on the number of overs a fast bowler may bowl in practice sessions and in matches. These workloads have not been based on any evidence based research. This is thus the first study that aims to quantify the volume of bowling that the developing musculoskeletal system is able to cope with before an injury results and thus provides coaches, trainers, fast bowlers, and parents with valuable information.

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Appendix 3 Paper submitted for publication in a peer-reviewed journal related to Chapter C1

Dennis, R.J., Hayen, A. and Finch, C.F. (2005). Determining the intra- and inter-observer reliability of screening tools used in sports injury research. *Journal of Science and Medicine in Sport,* (submitted – currently under review).

COVER PAGE

Title: Determining the intra- and inter-observer reliability of screening tools used in sports injury research

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Abstract:

Sports injury etiological studies explore the relationships between potential injury risk factors and injury outcomes. The ability of such studies to clearly identify intrinsic risk factors for sports injury depends on the accuracy of their measurement. Measurements need to be reproducible over time and repeatable by different observers, as well as within a given individual. The importance of the reliability of pre-participation screening protocols and other clinical assessment tools has been identified in a number of published studies. However, a review of these studies indicates that a variety of statistical techniques have been used to calculate intra- and inter-observer reliability. Whilst the intra-class correlation coefficient (ICC) is the most often cited measure, a range of statistical approaches to estimating the ICCs have been used. It is therefore difficult to determine which statistical method is most appropriate in the context of measuring intrinsic risk factors in sports injury research. This paper summarises a statistical method for the concurrent assessment of intra- and inter-observer reliability and presents an argument for why this is approach should be adopted by sports injury researchers using screening protocols that collect continuous data.

Determining the intra- and inter-observer reliability of screening tools used in sports injury research

The importance of reliability

Over recent years there has been an increasing call to provide a firm evidence base for sports injury prevention initiatives. As argued by Bahr and Krosshaug [1], provision of this evidence base is limited by knowledge about the etiological factors causing many sports injuries. To redress this imbalance, there needs to be considerably more effort put towards conducting studies to elucidate the intrinsic and extrinsic risk factors for sports injury.

Such studies naturally involve the measurement of potential risk factors and relating these to injury outcomes. In the prospective study ideal, measurements are made on participants in an injury-free state, eg. at the start of a playing season, and these are related to injury outcomes during the following participation period. For intrinsic risk factors, such as strength, flexibility, and balance, it is often of interest to see how these also vary over the playing season or how they differ in injured and uninjured participants at the end of the season. This necessitates taking multiple measurements.

The ability for such studies to clearly identify potential risk factors depends on the accuracy with which these measurements are made [2]. Measurements need to be reproducible over time and by different observers, as well as being repeatable within a given individual. Poor reproducibility limits the ability of researchers to reach conclusions about whether a measured variable is indeed a risk factor for injury, because it is difficult to differentiate participants with or without the variable of interest in the presence of large random measurement error [3].

Definition of reliability and its related concepts

Validity of measurement is the degree to which a test measures what it is supposed to measure [4] and reliability refers to the consistency, or repeatability, of a measure [4, 5]. Whilst a measure can be reliable without being valid, the reverse is not true [4, 6]. Low reliability indicates that large variations in measurement will occur upon retesting so that assessment outcomes cannot be meaningfully reproduced or interpreted [7]. Whilst factors such as weight and height are typically measured with high reliability, other potential injury risk factors, such as joint range of motion (ROM), may be more prone to unreliable measurement [2]. Another consequence of unreliability is the need for an increased sample size to detect an important difference between groups for the variable being measured; because of the increased variability in measurement [8]. This has obvious implications for the design of prospective cohort studies and randomised controlled trials that compare controls and intervention groups. In particular, this may result in an unnecessary increase in the cost and timing of conducting such studies.

In clinical assessments, measurement error can be introduced by the human observer (eg. a physiotherapist conducting a clinical assessment) and/or the instrument used (eg. a goniometer). Using the assessment of ROM as an example, if the goniometer has been shown to be reliable, then the reliability of the ROM measurements depends on the correct use of the goniometer by the physiotherapist. This paper deals specifically with the issue of determining the reliability of the human observer, which is the ability of a single observer or multiple observers to produce the same measurements consistently under the same conditions with the same sample [7, 9]. Two forms of observer reliability are discussed:

- intra-observer (or within observer) reliability - the degree to which measurements taken by the same observer are consistent

- inter-observer (or between observers) reliability - the degree to which measurements taken by different observers are similar.

Related to, but not identical to reliability, is the concept of precision. Precision is defined as the spread in random measurement error that would be expected if repeated independent observations are made on an individual [3]. It is a measure of absolute error, while reliability assesses the effect of that error on the ability to differentiate between individuals [3]. Obviously, if reliability is poor, it will not be possible to have precise measurements.

Purpose of this paper

The importance of the reliability of pre-participation screening protocols and other clinical assessment tools has been identified in a number of published studies [10-22]. As Table 1 shows, a variety of statistical techniques have been used to establish intra- and inter-observer reliability in these studies It is now generally accepted that the ICC is the measure of choice for determining reliability [23]. Whilst the intra-class correlation coefficient (ICC) has been the most often cited reliability measure, a range of models and methods to calculate the ICCs have been used. Many of the intraclass correlation coefficients given in able 1 are based on a popular set of methods described in Shrout and

Fleiss [25]. In many of the ways presented in that paper for calculating an intraclass correlation coefficient, such as the ICC(1,1), ICC(2,1) and ICC(3,1), it assumed that each observer takes only one measurement. This means that these methods cannot be applied to inter-observer reliability studies in which observers make more than one measurements [23]. Researchers also sometimes use the mean value of each observer's repeated measurements (Table 1), but this has the effect of inflating the inter-observer reliability as an ICC calculated from the mean of multiple measurements will be higher than that based on a single measurement [5, 8, 23]. It is also possible to just use the first of the repeated measurements taken by an observer, but this method is inefficient as it does not use all of the available information. Other studies have been limited because they have not stated the exact method they used to calculate the ICC.

<Insert Table 1 about here>

Because a variety of statistical methods to calculate reliability have been reported in the literature, or not stated at all, it is difficult to determine which method is most appropriate in the context of measuring intrinsic risk factors in sports injury research. The purpose of this paper, therefore, is to describe a particular statistical method (initially developed by Eliasziw and colleagues [23])for the concurrent assessment of intra- and inter-observer reliability and to describe why this is approach should be adopted by sports injury researchers using screening protocols that collect continuous data.

Data example

Whilst this paper does present statistical formulae, its emphasis is on providing information for application in future studies. To illustrate this, a real-world example of a reliability assessment of a musculoskeletal screening protocol used in a prospective cohort study of cricket fast bowlers is presented. The reliability assessment was conducted using two observers and 10 bowlers. The bowlers were each required to attend one appointment, in which they were tested by each observer twice (in the order of Observer 1, Observer 2, Observer 1, Observer 2). The tests were conducted in the same order each time, with 10-minute rest breaks between each session. The screening protocol consisted of a number of tests measuring flexibility, strength and stability. This assessment was approved by the University of New South Wales Human Ethics Review Committee.

Data from the reliability assessment of measurements of hip ROM have been extracted from the larger cricket study for the example in this paper. The range of hip rotation was assessed by physiotherapists with the hip in a neutral hip position. The bowler lay in a prone position with both knees bent to 90°, chin resting on the bench, arms by sides. Internal rotation was measured first and the bowler was asked to let both ankles move away from each other as far as possible, whilst the physiotherapist ensured that pelvic motion and/or hip flexion did not occur. To determine external rotation, the bowler straightened the contralateral knee and let the ankle of the testing leg drop towards the opposite side of the body as far as possible. An assistant to the physiotherapist measured the angle formed by the line of the tibia, relative to the vertical, as determined by a spirit level goniometer [24]. The angle was recorded to the nearest degree.

Notes on the statistical approach used

The reliability assessment example given in this paper used a short time interval to separate the testing sessions and it must be noted that the reliability of the measurements represents their reproducibility only within this particular time frame. Test-retest assessments within a short time interval tend to demonstrate higher reliability than those studies with longer time intervals, which may be influenced by a number of uncontrolled variables [9]. Although, reliability studies with short time intervals may be appropriate for those studies collecting pre-participation data, longer periods of time between assessments (eg. 1 week or 1 month) are important for clinical assessments where there is a need to evaluate patient improvements over time [9].

When conducting a reliability study, there are two main situations to consider:

1. the observers are assumed to have been drawn randomly from a larger population (*random observers*)

2. the observers are the only ones of interest (*fixed observers*).

This is an important distinction because the formulas for calculating the reliability differ slightly for these two scenarios. Our reliability assessment with two physiotherapists would be considered an example of *random observers*, because in our prospective study of fast bowlers, two physiotherapists conducted the musculoskeletal screening and the results had to be generalisable to a larger population of physiotherapists. In the clinical setting, for example,, two clinicians monitoring the progress of a patient may be the only people that will ever assess this patient. Hence, the results of a reliability assessment do not need to be applied to any other raters and the observers are fixed.

The method presented below has the distinct advantage over other methods (such as those of Shrout and Fleiss [25]) because it allows researchers to simultaneously assess inter- and intra-observer reliability.

Statistical methodology

In developing the statistical formulation below, it is important to define our terms from the outset. In the classical example, we have *m* repeated measurements made on a sample of *n* subjects by *o* different observers, so that there are *m*×*n*×*o* measurements in total. Although we speak of observers, one can use synonymous terms, such as raters or instruments, depending on the context.

The *k*th (k=1, …, m) measurement taken by the *j*th (j= 1,…, o) observer on the *i*th (i=1, …, n) subject is denoted by Y_{ijk}. Assessing reliability is essentially a repeated measures design and we can represent each of our observations according to the following repeated measures design:

$$Y_{ijk} = \mu + S_i + O_j + (SO)_{ij} + e_{ijk} ,$$

where μ is the mean of all possible measurements, S_i is the effect of subject *i*, O_j is the effect of observer *j*, $(SO)_{ij}$ is the inter-observer (or across observer) random error (or hetereogeneity), and e_{ijk} is the intra-observer random error (or within observer). We assume that S_i and e_{ijk} follow normal distributions with mean zero and variances σ_s^2 and σ_e^2 respectively. When assuming *random observers*, it is also necessary to assume that O_j and $(SO)_{ij}$ come from normal distributions with zero means and variance σ_O^2 and σ_{SO}^2 respectively. In the *fixed observer* case, the components O_j and $(SO)_{ij}$ are constrained so that $\sum_{j=1}^{o} O_j = \sum_{j=1}^{o} (SO)_{ij} = 0$. In addition, $(SO)_{ij}$ is assumed to follow a normal distribution with mean zero and variance $(o-1)\sigma_{SO}^2 / o$ (such constraints are for technical reasons only.

Estimates of the variance components can be obtained from an analysis of variance table (Table 2). From these tables, the variance components can be estimated by subtraction. For example, for *random observers*, σ_{SO}^2 can be estimated as $(\mathrm{MSO} - \mathrm{MSE}) / m$, which is obtained using subtraction in Table 2. The other variance components can be estimated similarly using the table. In some cases, these variance components may be calculated as a negative number, in which case they should be set to zero.

<Insert Table 2 about here>

Definition of the ICC

In this paper, the definition of the intraclass correlation coefficient (ICC) is the ratio of a covariance term and a variance term, in accordance with the usual definition of correlation coefficients. The ICC ranges from zero, when all observed differences between participants are caused by measurement error, to one when the ability to distinguish participants from each other based on the variable of interest is not at all influenced by random error [3]. Therefore, an ICC equal to, or close to, one is the desired result when determining the reliability of clinical assessment tools. As pointed out by Eliasziw et al [23], this definition is not the same as that used by other authors (eg. Fleiss [8]), who define intraclass correlation coefficients as ratios of variance components. However, the method described here allows the simultaneous assessment of inter- and intra-observer reliability, which is not directly possible when using the other methods.

The case of *random observer*s

The interclass correlation coefficient for *inter-observer* reliability is:
$ICC_{\text{inter}} = \text{cov}(Y_{ijk}, Y_{ilk}) / \text{var}(Y_{ijk})$, where *j* and *l* refer to different observers. This may then be estimated using the formula:

$$\hat{ICC}_{\text{inter}} = \frac{\hat{\sigma}_S^2}{\hat{\sigma}_S^2 + \hat{\sigma}_O^2 + \hat{\sigma}_{SO}^2 + \hat{\sigma}_e^2}$$

Each of the variance components may be estimated from Table 1.

For *intra-observer* reliability, the formula is $ICC_{\text{intra}} = \text{cov}(Y_{ijk}, Y_{ijl}) / \text{var}(Y_{ijk})$, where *k* and *l* refer to different measurements taken by the same observer on the same subject. This may be estimated using the formula

$$\hat{ICC}_{\text{intra}} = \frac{\hat{\sigma}_S^2 + \hat{\sigma}_O^2 + \hat{\sigma}_{SO}^2}{\hat{\sigma}_S^2 + \hat{\sigma}_O^2 + \hat{\sigma}_{SO}^2 + \hat{\sigma}_e^2}$$

The case of *fixed observers*

Just as in the case above, the reliability coefficients are calculated as the ratio of a covariance and a variance term. However, we now need to use the right hand side of Table 2 to estimate the reliability coefficients, and so the formulas for the calculating the ICC is different in this case. The formulas are:

$$\hat{ICC}_{\text{inter}} = \frac{\hat{\sigma}_S^2 - \hat{\sigma}_{SO}^2 / o}{\hat{\sigma}_S^2 + (o-1)\hat{\sigma}_{SO}^2 / o + \hat{\sigma}_e^2}$$

and

$$\hat{ICC}_{\text{intra}} = \frac{\hat{\sigma}_S^2 + (o-1)\hat{\sigma}_{SO}^2 / o}{\hat{\sigma}_S^2 + (o-1)\hat{\sigma}_{SO}^2 / o + \hat{\sigma}_e^2}$$

Once again, each of the estimates of the variance components can be estimated through the use of subtraction from Table 1.

Hypothesis tests

Hypothesis tests can be easily used to test whether the observed reliability meets a specified level [23, 25]. There are no universally applicable standards as to how high the ICC must be to constitute acceptable reliability, as this depends on the purpose, the use and consequences resulting from the assessment [7]. For example, an ICC of 0.6 may be considered appropriate within the context of a pre-participation screening for sports injury research. However, this may not be appropriate for a clinical assessment that will directly influence the choice of treatment for a patient. It should be noted that it is usually appropriate only to consider one sided hypothesis tests to determine whether the observed reliability coefficients meet a specified level of reliability.

The hypothesis test for the *inter-observer* ICC is as follows: the null hypothesis as $H_0 : ICC \le \lambda$ and the alternative as $H_1 : ICC > \lambda$, where λ is a specified value between 0 and 1. The test statistic is

$$F_{\text{inter}} = \frac{1-\lambda}{1+((o-1)\lambda)} \times \frac{MSS}{MSSO},$$

which may be compared against an F distribution with degrees of freedom (n-1) and (n-1)(o-1). Although this test statistic applies to both fixed and random observer effects, the relevant mean squares (MMS and MSSO) need to be taken from the appropriate part of Table 1.

Similarly, for the *intra-observer* reliability, a test of the hypothesis $H_0 : ICC \le \lambda$ against the alternative $H_1 : ICC > \lambda$, where λ is between 0 and 1, has the test statistic

$$F_{\text{intra}} = \frac{1-\lambda}{1+\left((m-1)\lambda\right)} \times \frac{MSS/o}{MSSO},$$

which may be compared with an F distribution with degrees of freedom (n-1) and n(m-1). Again, this test statistic applies to either fixed or random observer effects, but, as before, the appropriate mean squares need to be used from table 1.

Confidence intervals and sample size

Although it is possible to calculate confidence intervals for ICCs, the formulas are long and complicated, and are therefore included as an addendum to this paper.

It is beyond the scope of this paper to discuss the sample sizes needed for reliability studies, though it is emphasised that this should be taken into account in their design. To obtain precise estimates of reliability coefficients, it is important to enrol an adequate number of subjects into a trial. The reader is referred to the paper by Walter and colleagues [26] for details of these calculations.

A worked example – the reliability of the hip external rotation test

To illustrate the application of these formulas to a real world example, we use our example of determining the ICC of a test of hip external rotation, with two observers testing 10 participants; this is a *random observer* case. The calculated analysis of variance table for this example is given in Table 3, from which estimates of the variance components can be calculated. Using this table, we see directly that MSE= $\hat{\sigma}_e^2$ = 9.05. Now, using Table 2 and subtraction, $\hat{\sigma}_{SO}^2 = (33.46 - 9.05)/2 = 12.20$. Similarly, we obtain $\hat{\sigma}_S^2 = 48.65$ and $\hat{\sigma}_O^2 = 3.45$. Substitution of these values into the formulas for random observers gives $\hat{ICC}_{\text{inter}} = 0.66$ and $\hat{ICC}_{\text{intra}} = 0.88$.

To perform a hypothesis test to see if $H_0 : ICC_{\text{inter}} \leq 0.2$ versus the alternative as $H_1 : ICC_{\text{inter}} > 0.2$, then substitution of values gives a test statistic 4.54, which is compared against an *F* distribution with degrees of freedom 9 and 9, yielding a p-value of 0.02. Thus we have evidence that the reliability of our test is at least fair.

We can also calculate a confidence interval for the inter- and intra-observer reliability. Details of the calculation are given in the addendum. For *inter-observer* reliability, we obtain a 95% CI 0.253 to 0.896. For *intra-observer* reliability, the 95% CI is 0.539 to 0.961.

Finally, if the mean of each observer's ratings was used to calculate the inter-observer reliability using the ICC(2,1) formula of Shrout and Fleiss [23], the estimated inter-observer reliability would be 0.918, which is much higher than that based on the individual observations. However, this is the reliability of the mean of two measurements, and not the reliability of individual measurements.

Concluding remarks

Sports injury prevention requires a firm evidence base. An important component of this is the accuracy and reliability of measurements taken in studies of risk factors. When measurements are not reliable, it is difficult to distinguish between participants with or without risk factors because of the large measurement error.

In this paper, a method for the simultaneous assessment of inter- and intra-observer reliability has been given. Unlike many other popular methods in the literature, this method is valid for the calculation of both inter-observer and intra-observer reliability in the same study.

References

1. Bahr, R. and T. Krosshaug, *Understanding injury mechanisms: a key component of preventing injuries in sport.* Br J Sports Med, 2005. **39**(6): p. 324-329.
2. Bahr, R. and I. Holme, *Risk factors for sports injuries - a methodological approach.* British Journal of Sports Medicine, 2003. **37**(5): p. 384-392.
3. Haas, M., *How to evaluate intraexaminer reliability using an interexaminer reliability study design.[erratum appears in J Manipulative Physiol Ther 1995 Jul-Aug;18(6):434].* Journal of Manipulative & Physiological Therapeutics, 1995. **18**(1): p. 10-5.

4. Thomas, J.R. and J.K. Nelson, *Measuring research variables*, in *Research methods in physical activity*. 1996, Human Kinetics: Champaign, USA.
5. Hopkins, W.G., *Measures of reliability in sports medicine and science.* Sports Medicine, 2000. **30**(1): p. 1-15.
6. Batterham, A.M. and K.P. George, *Reliability in evidence-based clinical practice: a primer for allied health professionals.* Physical Therapy in Sport, 2003. **4**(3): p. 122-128.
7. Downing, S.M., *Reliability: on the reproducibility of assessment data.* Medical Education, 2004. **38**(9): p. 1006-12.
8. Fleiss, J.L., *Reliability of measurement*, in *The design and analysis of clinical experiments*. 1986, John Wiley & Sons: New York.
9. Gajdosik, R.L. and R.W. Bohannon, *Clinical measurement of range of motion. Review of goniometry emphasizing reliability and validity.* Physical Therapy, 1987. **67**(12): p. 1867-72.
10. Gabbe, B.J., et al., *Reliability of common lower extremity musculoskeletal screening tests.* Physical Therapy in Sport, 2004. **5**(2): p. 90-97.
11. Holmich, P., L.R. Holmich, and A.M. Bjerg, *Clinical examination of athletes with groin pain: an intraobserver and interobserver reliability study.* Br J Sports Med, 2004. **38**(4): p. 446-451.
12. Scott, D.A., et al., *The intra- and interrater reliability of hip muscle strength assessments using a handheld versus a portable dynamometer anchoring station.* Archives of Physical Medicine & Rehabilitation, 2004. **85**(4): p. 598-603.
13. Click Fenter, P., et al., *Reliability of stabilised commercial dynamometers for measuring hip abduction strength: a pilot study.* British Journal of Sports Medicine, 2003. **37**(4): p. 331-334.
14. McKenna, L., J. Cunningham, and L. Straker, *Inter-tester reliability of scapular position in junior elite swimmers.* Physical Therapy in Sport, 2004. **5**(3): p. 146-155.
15. Maulder, P. and J. Cronin, *Horizontal and vertical jump assessment: reliability, symmetry, discriminative and predictive ability.* Physical Therapy in Sport, 2005. **6**(2): p. 74-82.
16. Stockbrugger, B.A. and R.G. Haennel, *Validity and reliability of a medicine ball explosive power test.* Journal of Strength & Conditioning Research, 2001. **15**(4): p. 431-8.

17. Herrington, L.C., *The inter-tester reliability of a clinical measurement used to determine the medial-lateral orientation of the patella.* Manual Therapy, 2002. **7**(3): p. 163-7.

18. Tousignant, M., et al., *Intratester and intertester reliability of the Cybex electronic digital inclinometer (EDI-320) for measurement of active neck flexion and extension in healthy subjects.* Manual Therapy, 2001. **6**(4): p. 235-41.

19. Peolsson, A., R. Hedlund, and B. Oberg, *Intra- and inter-tester reliability and reference values for hand strength.* Journal of Rehabilitation Medicine, 2001. **33**(1): p. 36-41.

20. Bennell, K.L., et al., *Intra-rater and inter-rater reliability of a weight-bearing lunge measure of ankle dorsiflexion.* Australian Journal of Physiotherapy, 1998. **44**(3): p. 175-180.

21. Clark, N.C., et al., *Intratester reliability and measurement error of the adapted crossover hop for distance.* Physical Therapy in Sport, 2002. **3**(3): p. 143-151.

22. Young, W., et al., *An evaluation of the specificity, validity and reliability of jumping tests.* Journal of Sports Medicine & Physical Fitness, 1997. **37**(4): p. 240-5.

23. Eliasziw, M., et al., *Statistical methodology for the concurrent assessment of interrater and intrarater reliability: using goniometric measurements as an example.* Physical Therapy, 1994. 74(8): p. 777-88.

24. Harvey, D., Screening test protocols: pre-participation screening of athletes: a program developed by the Australian Institute of Sport, Olympic Athlete Program and the Australian Sports Injury Prevention Taskforce. 1998, Canberra, Australia: Australian Sports Commission.

25. Shrout, P.E. and J.L. Fleiss, Intraclass correlations: Uses in assessing rater reliability. Psychological Bulletin, 1979. 86(2): p. 420-428.

26. Walter, S.D., M. Eliasziw, and A. Donner, Sample size and optimal designs for reliability studies. Statistics in Medicine, 1998. 17(1): p. 101-10.

Table 1 Overview of the methods used to determine inter-observer and/or intra-observer reliability in published research

Authors		Data collection	Inter-observer	Intra-observer	How calculated
Gabbe et al [10]	Lower extremity musculoskeletal screening tests	2 raters, 15 subjects, 2 sessions, 2 trials per rater per session	ICC (2,1)	ICC (3,1)	Used mean of two trials per rater
Scott et al [12]	Comparison of two dynamometers assessing hip muscle strength	2 raters, 15 subjects, 2 sessions, 3 trials per rater per session	ICC – calculated from 2 way mixed analysis of variance	ICC – 1 way random effects analysis of variance.	Used mean of three trials, as well as maximal value of the 3 trials
Click Fenter et al [13]	Comparison of three dynamometers measuring hip abduction strength	2 raters, 10 subjects,1 session, 2 trials per rater	ICC (2,1)	ICC (2,1)	Not clear from the presented information
McKenna et al [14]	Clinical examination technique for scapula position	3 raters, 15 subjects, 1 session, 1 trial per rater	ICC (2,1)	n/a	Compare raters using mean scores for 10 subjects across four arms positions
Maulder et al [15]	Comparison of six horizontal and vertical jump tests	6 tests, 10 subjects, 2 sessions, 3 trials per test per session	Inter-class correlation coefficient but no method for calculation is given	n/a	Compare the 6 tests using mean scores for all 10 subjects
Stockbrugger et al [16]	Medicine ball explosive power test	1 test, 20 subjects, 2 sessions, 3 trials per session	ICC (r1)	n/a	Used best score from each session for comparison
Herrington [17]	Clinical	20 raters, 1	Inter-class correlation	n/a	Used mean of 3

	examination technique to determine orientation of the patella	subject, 1 session, 3 trials per rater	coefficient but no method for calculation is given		trials
Tousignant et al [18]	Use of an inclinometer to measure neck flexion and extension	2 raters, 44 subjects, 2 sessions, 1 trial per rater per session	ICC (2,1)	ICC (1,1)	Used mean of two trials for inter-observer
Peolsson et al [19]	Use of a dynamometer to measure handgrip strength	3 raters, 32 subjects, 1 session, 3 trials per rater	ICCs were calculated using repeated measures one-way ANOVA.	ICCs were calculated using repeated measures one-way ANOVA	Not mentioned
Bennell et al [20]	Weight-bearing lunge measure of ankle dorsiflexion	13 subjects. Inter-observer: 4 raters, 1 session, 3 trials per rater. Intra-observer: 2 raters, 2 sessions, 3 trials per rater per session	ICC (2,3)	ICC (3,3)	Mean of 3 trials used
Clark et al [21]	Adapted crossover hop for distance	1 observer, 12 subjects, 2 sessions, 3 trials per session	NA	ICC (2,1)	Maximum hop distance was used
Young et al [22]	Comparison of two methods of measuring vertical jump height	2 methods of assessment (observers), 17 subjects, 2 sessions, 3 trials per session	Paired t-tests	n/a	

Table 2: Expected mean square values from a two-way analysis of variance

			Random observer case	Fixed observer case
Source of variation	Degrees of freedom	Observed mean square	Expected mean square	Expected mean square
Subjects	n-1	MSS	$mo\sigma_S^2 + m\sigma_{SO}^2 + \sigma_e^2$	$mo\sigma_S^2 + \sigma_e^2$
Observers	o-1	MSO	$mn\sigma_O^2 + m\sigma_{SO}^2 + \sigma_e^2$	$mn\sum_{j=1}^{o} O_j^2 /(o-1) + m\sigma_{SO}^2 + \sigma_e^2$
Subjects × observers	(n-1)(o-1)	MSSO	$m\sigma_{SO}^2 + \sigma_e^2$	$m\sigma_{SO}^2 + \sigma_e^2$
Error	no(m-1)	MSE	σ_e^2	σ_e^2
Total	mno-1			

Table 3: Analysis of variance table for determining inter- and intra-observer reliability for hip external rotation in cricket fast bowlers

Source of variation	**Degrees of freedom**	**Sum of squares**	**Observed mean square**
Subjects	9	2052.60	228.07 (MSS)
Observers	1	102.40	102.40 (MSO)
Subjects × observers	9	301.10	33.46 (MSSO)
Error	20	181.00	9.05 (MSE)
Total	29		

Appendix 4 Approval for the study presented in Chapter B1

AUSTRALIAN CRICKET BOARD

18 September 2000

Ms Rebecca Dennis
4/64 Weston St
Harris Park
NSW 2150

Dear Rebecca,

Thank you for presenting at the ACB's Cricket, Sports Science and Medicine Forum held in Melbourne on the 22nd and 23rd August 2000.

Your presentation of your study on *Bowling Workload and Injury* was well received by the Forum. As you are aware one of the key recommendations arising from the Forum was that a national Bowling Workload study be undertaken in 2000/2001 to validate the findings of the pilot research program.

I wish to advise that at its meeting on 8 September 2000 the ACB Directors approved a proposal for a national study to further investigate the relationship between bowling workload and injury.

I will write to you again to set out the parameters of the national research program in the near future.

Finally, I wish to extend appreciation on behalf of the Australian Cricket Board for your outstanding work and presentation.

Yours sincerely,

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Appendix 5 Information statement and consent form for the study presented in Chapter B1

National Fast Bowling Workload and Injury Study

In 1999-2000 a study was conducted with the NSW Blues to establish the relationship between the total bowling volume of fast bowlers and the incidence, nature and severity of injuries sustained. The results obtained indicate a consistent relationship between workload and injury. However, in order to obtain statistically significant results, the study needs to be continued on a much larger scale.

Following presentation of these results to the Cricket Sports Science and Medicine Forum, the Australian Cricket Board awarded a research grant for this study to be continued with all first-class fast bowlers in Australia.

We want to determine how the frequency and amount of bowling affects a player’s risk of sustaining an injury. Basically, we are trying to establish if there is a “safe” fast bowling workload threshold.

To do this, it is necessary to quantify the total bowling workload of every first-class fast bowler in Australia. This includes monitoring bowling in matches, warm-up for matches and training sessions.

We are asking for your assistance in ensuring this research project obtains accurate results by providing the following information:

A record of your grade training bowling

An estimate of your match day warm-up deliveries

Each week the research assistant working on this study will provide you with a log sheet to record any bowling you do at grade training sessions. It is vital for the success of this project that you record this information and return it to the assistant at the next scheduled State Squad training session.

We also need to know the average number of warm-up deliveries you usually bowl on a match day. Please record this estimate at the bottom of the page.

Your participation and cooperation in this project will ensure that the most accurate results possible are obtained. The information obtained from this study will be vital in developing injury prevention strategies for fast bowlers; as it may be possible to identify a “safe” bowling threshold. Guidelines for the amount and frequency of bowling will then be developed for fast bowlers to ensure that the risk of injury is as low as possible.

This research project is being conducted by Rebecca Dennis and Patrick Farhart with the support of the ACB and State Associations. If you need any further information, please contact Patrick on 0418 967 618.

Consent

In signing this consent form I agree that I have read the information leaflet regarding this research project and agree to participate.

Name ____

Signature ____

Date _________________

Grade club ____

Usual number of match warm-up deliveries _____________________

Appendix 6 Grade club training logbook for the study presented in Chapter B1

National Fast Bowling Workload and Injury Study

Grade Training Workload Diary

Name ______________________

State ______________________

Date	Number of deliveries

Appendix 7 Approval for the study presented in Chapter B2

4.FEB.2005 9:08 NO.538 P.2/2

Australian Institute of Sport
Sport Sciences

MINUTE

TO:	Marc Portus	**CC:**	
FROM:	John Williams		
SUBJECT:	Approval from AIS Ethics Committee		
DATE:	17th August 2001		

Marc,

I am pleased to inform you that at the last meeting of the AIS Ethics Committee held on 14th August 2001, the Committee agreed that there were no ethical reasons why your project ***Trunk biomechanics, core strength and bowling workload as a function of trunk injury in Australian cricket fast bowlers*** should not proceed, subject to you providing the Committee with a revised Clearance Requirements Questionnaire (reflecting the inclusion of MRI testing).

It is a requirement of the AIS Ethics Committee that all researchers notify the Committee (via the Secretary) of:

any changes to the research design,
any adverse events that may occur,
termination of the project and/or eventual completion of the study.

The Committee also requests a brief summation of the outcomes of the study and the manner in which the outcomes are presented (eg, journal articles, reports, seminars etc)

If you have any questions regarding this matter, please don't hesitate to contact me on (02) 6214 1816.

Sincerely

John Williams
Secretary, AIS-EC

Appendix 8 Information statement and consent form for the study presented in Chapter B2

Information for participants in the ACB "SPOT" research 2002-03

Project Title: The influence of fast bowling technique, lumbo-pelvic stability and bowling workload on trunk injury in cricket fast bowlers (ACB "SPOT" research).

Principal Researchers: Marc Portus, Patrick Farhart, Rebecca Dennis, Dr. John Orchard (Australian Cricket Board).

Supervisors/Co-investigators: Dr. Bruce Mason – AIS Biomechanics, Professor Bruce Elliott - UWA, Dr. David Lloyd - UWA, Dr. Howard Galloway – Canberra Hospital, Dr. David Pyne – AIS Physiology.

Purpose
The purpose of this research project is to further understand the causes of the high incidence of fast bowling trunk injuries in cricket. From the findings of this study we hope to enable young developing fast bowlers, and those well established in the higher levels of the game, to continue to bowl with a reduced risk of injury and pain in the trunk region.

Procedures
To do this we need to study a collection of junior and senior fast bowlers for season 2002-03. If you decide to participate in this project we will assess your bowling technique, flexibility, body dimensions, strength and power at the Australian Institute of Sport in Canberra in October or November 2002. You will be required to attend a 2-day camp at the AIS in Canberra for us to collect this information from you. At this camp you will have six (6) appointments to attend. Five of these will be at the AIS Sports Science Sports Medicine Building and one will be at John James Hospital. We will plan all your appointments and transport to John James Hospital and inform you of your schedule. The Australian Cricket Board will provide all transport, meals and accommodation at the AIS Halls of Residences for all participants not residing in Canberra. Brief details about the six appointments follow.

Bowling and dynamic stability assessment
The assessment of your bowling technique will involve you bowling in the AIS Biomechanics Laboratory at match pace for no more than 3 overs. To measure aspects of your technique we will place small reflective balls on selected anatomical landmarks (e.g. shoulders, back, legs) and film you bowling. We will also measure your impact forces during the delivery stride with force plates in the laboratory floor. While in the AIS Biomechanics Laboratory we will also ask you to perform a series of simple movements such as hops and circling of your arms. We will video record these movements to help us analyse your body dimensions and lumbo-pelvic stability.

Anthropometric assessment
Anthropometry is the assessment of your body dimensions and composition. This assessment will include measures such as the length of your arms, the girth of your chest and your skinfolds. This will occur in the AIS Physiology Laboratory.

Power assessment
Also in the AIS Physiology Laboratory you will have your power assessed. This will involve you throwing a bar with a light weight on it. We will measure how far you can throw the bar.

We also get you to jump with the bar on your shoulders. We will also measure how high you can jump with this light weight across your shoulders.

KinCom trunk flexion-extension assessment
A trunk flexion-extension strength test will be carried out in the AIS Physiotherapy department. This machine (KinCom Dynamometer) is specifically designed to measure strength imbalances from side to side or front to back. You will sit in a chair like device and exert force against a padded bar. From this the KinCom will report the strength ratio between your trunk flexors and your trunk extensors.

Physiotherapy musculoskeletal screen
A sports physiotherapist will assess a range of factors relating to your musculoskeletal condition. This will include measures of your shoulder, trunk and hamstring flexibility as well as your lumbo-pelvic stability. This will be very similar to a standard sports physiotherapy assessment.

Magnetic Resonance Imaging (MRI)
Whilst in Canberra you will be driven to John James Hospital for a Magnetic Resonance Imaging Scan (MRI) of your lower back and trunk. This is a standard non-invasive medical screening procedure. It is like having an X-ray except MRI's do not utilise radiation and hence do not cause you any harm or side effects. These MRI's will be performed by Canberra Imaging Group under the supervision of an experienced Radiologist.

During the cricket season
During season 2002-03 we will also be counting the number of balls you bowl during practice and in matches. We will need you to be willing to help us track your bowling workload. For junior bowlers a member of our research team will contact you and/or your coach weekly to update your bowling workload information. For senior bowlers there will be a workload monitor present at your state squad practice sessions.

We will also need to evaluate any injury you suffer to your trunk region during the cricket season. A sports physician in your home city will be designated by us to perform an evaluation of any trunk injury that you may suffer. If the sports physician deems it necessary for you to have a second MRI for injury diagnosis as part of the research this will also be performed in your home city by an experienced Radiologist. If you do not become injured in the trunk region during the 2002-03 cricket season you will be required to have a second MRI at the completion of the season (March 2003) in your home city. These costs are covered by the ACB as part of this research project.

Please note the Australian Cricket Board, or any other party associated with this research project, cannot cover treatment or rehabilitation costs for any injuries you sustain during the 2002-03 cricket season.

Risks to you
The testing procedures outlined above are standardised biomechanical, physiotherapy and fitness assessment procedures and pose little risk of causing you any physical or mental harm or injury. You may experience delayed onset muscle soreness resulting from the strength/power tests, as with any exercise that you may be unaccustomed to performing. Magnetic Resonance Imaging Scans (MRI) do not utilise radiation and hence do not pose any risk.

Benefits
These procedures are entirely experimental and they are not intended to provide any specific technical assessment, medical diagnosis or treatment to you. By participating in the research,

you will benefit by the close monitoring of the condition of your trunk and back, with special consideration given to the development of signs of trunk side strains, lower back soft tissue injuries and lumbar spine stress fractures. You will also experience the procedures and facilities utilised at the Australian Institute of Sport for sports science research and elite athlete development.

This research program offers benefits to the cricket, medical and general community. However, the advancement of medically related research is dependent on the generosity of individuals in donating their time. It is hoped that this study will further our understanding of the causes of trunk injuries in junior and senior fast bowlers in cricket. This in turn will make cricket a safer and more enjoyable sport to play for junior players and hopefully allow senior bowlers to continue their careers with a reduced likelihood of injury and pain.

Participant rights
Participation in this research is voluntary and you are free to withdraw from the study at any time and for any reason, without prejudice in any way. Your participation in this study does not prejudice any right you may have under statute of common law. The information we collect from you will remain anonymous in the public domain, except to the researchers listed above, and we encourage you to ask questions about anything you feel unsure about. Further information is available from:

Marc Portus
Australian Cricket Board Sports Science Officer
Australian Institute of Sport Biomechanics Department
Ph: (02) 6214 1559
Fax: (02) 6214 1593
Email: marc.portus@ausport.gov.au

Informed Consent Form – ACB "SPOT" Research 2002-03

Project Title: The influence of fast bowling technique, lumbo-pelvic stability and bowling workload on trunk injury in cricket fast bowlers.

Principal Researchers: Marc Portus, Patrick Farhart, Rebecca Dennis, Dr. John Orchard (Australian Cricket Board)

Supervisors/Co-investigators: Dr. Bruce Mason – AIS Biomechanics Department; Professor Bruce Elliott – School of Human Movement and Exercise Science, The University of Western Australia; Dr. David Lloyd - School of Human Movement and Exercise Science, The University of Western Australia; Dr. Howard Galloway – Canberra Hospital; Dr. David Pyne – AIS Physiology Department.

This is to certify that I, ______________________________ hereby agree to (give permission to have my child) participate as a volunteer in a scientific investigation as an authorised part of the research program of the Australian Cricket Board and Australian Sports Commission under the supervision of Marc Portus and Patrick Farhart.

The investigation and my (child's) part in the investigation have been defined and fully explained to me by __________________________ and I understand the explanation. A copy of the procedures of this investigation and a description of any risks and discomforts has been provided to me and has been discussed in detail with me.

- I have been given an opportunity to ask whatever questions I may have had and all such questions and inquiries have been answered to my satisfaction.
- I understand that I am (the child is) free to withdraw consent and to discontinue participation in the project or activity at any time.
- I understand that any data or answers to questions will remain confidential with regard to my (child's) identity.
- I certify to the best of my knowledge and belief, I have (the child has) no physical or mental illness or weakness that would increase the risk to me (him/her) of participating in this investigation.
- I am (the child is) participating in this project of my (his/her) own free will and I have (the child has) not been coerced in any way to participate.

Signature of Participant: _____________________________ Date: ___/___/___

Date of Birth: ___/___/______

Signature of Parent or
Guardian of minor: _______________________________ Date: ___/___/___

I, the undersigned, was present when the study was explained to the subject/s in detail and to the best of my knowledge and belief it was understood.

Signature of Researcher: ___________________________ Date: ___/___/___

Appendix 9 Bowling workload logbook for the study presented in Chapter B2

Australian Cricket Board
SPOT research project 2002-2003
Weekly bowling workload recording sheet
Please return to Rebecca Dennis via email at becdennis@bigpond.com or fax to 02 4577 6761
For further information please call Rebecca on 0418 484 399

PLAYER: ____________________ **D.O.B:** / /

KEY:
Surface: T = turf, S = synthetic, I = indoor
Intensity: H = hard (full run-up, match intensity), M = medium (shorter run-up, controlled pace), L = light (short/ no run-up, technique work)

TRAINING: (one row per session)

DETAILS					COMMENTS
Date	Squad / Team	Surface (T, S, I)	Intensity (H, M, L)	Balls Bowled	(eg injuries, conditions, general feeling etc)

MATCHES: (one row per innings)

DETAILS					COMMENTS
Date	Team	Surface (T, S, I)	Full Statistics (O-M-R-W)	Balls Bowled	(eg injuries, conditions, general feeling etc)

Appendix 10 Information statement and consent form for the study presented in Chapter B3

THE UNIVERSITY OF
NEW SOUTH WALES

The School of Safety Science

THE UNIVERSITY OF NEW SOUTH WALES, CRICKET AUSTRALIA and CRICKET NSW

PARENTAL (OR GUARDIAN) INFORMATION STATEMENT

Cricket Fast Bowling Workload, Injury and Performance Project

Dear Parent/Guardian,

Researchers from The University of New South Wales, in conjunction with Cricket Australia and Cricket NSW, are conducting a study that examines various measures of fast bowling workload and how they affect the risk of injury and bowling performance. From the findings of this study we hope to develop guidelines to reduce the risk of injury and maximise bowling performance for all high performance fast bowlers. This project is being conducted by Professor Caroline Finch, Dr Andrew McIntosh, Professor Bruce Elliott and Ms Rebecca Dennis.

We have contacted your child/dependent about this study because Cricket NSW has agreed, in principle, to participate in the project and your child/dependent has been identified as a member of a high performance squad with this association. We would therefore like to invite your child/dependent to participate in this research project.

Procedures
If you permit your child/dependent to participate, they will be required to undergo a series of physical tests at the start and end of the season, complete a bowling workload diary for the duration of the 2003-04 summer season as well as to complete a short questionnaire about his bowling performance in matches throughout the season. He will also be asked to complete a survey which asks him questions such as his age when he commenced fast bowling, previous injury history and any other sports in which he may participate. Details about each of the requirements are outlined below.

Bowling technique assessment
The assessment of your child/dependent's bowling technique will involve him bowling at the indoor facilities of Cricket NSW at a match pace for no more than 3 overs. We will video record this session to help us assess his technique and bowling speed. This bowling assessment will be conducted at the start and end of the season and will take approximately 20 minutes.

Physiotherapy screening

A physiotherapist will assess a range of factors relating to your child/dependent's muscles and body joints in a 30-minute series of tests at the start and end of the season. This will include testing the flexibility of his shoulders and hips, the strength of his upper and lower body, the strength of his back and abdominal muscles.

Fitness and strength testing

A fitness advisor will assess factors such as your child/dependent's general fitness, running speed, leg power, and upper body strength in a 30-minute series of tests at the start and end of the season. We will also conduct tests which measure things such as his height and weight, the lengths of his arms and legs and how much body fat he has.

During the cricket season

During the 2003-04 season, your child/dependent will be required to count the number of balls he bowls during every training session and in all matches and to complete a daily bowling workload diary. This diary will then need to be submitted each week either by entering the information onto a Cricket Australia internet site or returned via email, fax or mail. This information will be checked by an assistant who will attend random match and training sessions throughout the season.

We will also ask your child/dependent to complete a short questionnaire to rate his bowling performance in areas such as concentration, bowling to a plan, rhythm, control, line and length for each match in which he bowls. Your child/dependent's coach will also be asked to complete a similar questionnaire to rate his bowling performance in chosen matches. For bowlers in selected squads, we will also access the videotapes of selected matches routinely recorded by his state cricket association so we can assess his performance. This is so we can compare information recorded on the tapes, with the information that he provides in the questionnaire.

If your child/dependent sustains an injury during the season, he will be required to record this on his bowling workload diary. A sports physician or physiotherapist at your state cricket association will then arrange to meet or call him to discuss this injury. This is so we can record the type of injury he has sustained, what part of the body it has affected and how the injury occurred. His state cricket association will determine if any treatment or further advice for this injury is to be given by the association.

Risks to your child/dependent

The testing procedures outlined above are standardised biomechanical, physiotherapy and fitness assessment procedures and pose little risk of causing your child/dependent any physical or mental harm or injury. Where possible, these tests will be conducted during regular training sessions/camps that he is already required to attend to minimise any inconvenience to you and your child/dependent. He may experience minor delayed onset muscle soreness resulting from the strength/power tests, as with any exercise that he may be unaccustomed to performing.

Benefits

These procedures are entirely experimental and they are not intended to provide any specific technical assessment, medical diagnosis or treatment to your child/dependent. This research program offers benefits to the cricket, medical and general community. However, the advancement of medically related research is dependent on the generosity of individuals in donating their time. It is hoped that this study will further our understanding of the causes of overuse injuries in junior and senior fast bowlers. This in turn will make cricket a safer and more enjoyable sport to play for fast bowlers and hopefully allow your child/dependent and future players to maintain a career in fast bowling with a reduced likelihood of injury. It will also ensure that Australia is well-equipped with a pool of fit, healthy and high performing fast bowlers.

Use of information and participant rights

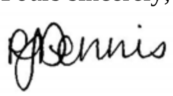
Results obtained in this study and information obtained from your child/dependent during the season will be made available to Cricket Australia as well as Cricket NSW. However, no findings which could identify him specifically will be published or released in the public domain. The combined results of all participants may be presented at scientific conferences or published in a peer-reviewed journal, however will they not identify individual bowlers. All of your child/dependent's personal information will be de-identified, by use of a code number, to ensure his records remain anonymous. Only the investigators named above will have access to the coded data which will be stored for at least seven years as prescribed by the university regulations. Your child/dependent may access the information recorded about him during the 2003-04 season upon request.

Participation in this research is entirely voluntary. If you agree for your child/dependent to participate you (on behalf of your child/dependent) are free to withdraw at any time and for any reason. Declining to participate in the study or withdrawing from the study at any time, will in no way affect your child/dependent's standing with The University of New South Wales, Cricket Australia or Cricket NSW. Complaints may be directed to the Ethics Secretariat, The University of New South Wales, SYDNEY 2052 AUSTRALIA (phone 02 9385 4234, fax 02 9385 6648, email ethics.sec@unsw.edu.au).

Attached is a consent form for you to sign to indicate your acceptance for your child/dependent to participate in the study.

The combined results of this study will be made available to your child/dependent on completion of the study through Cricket Australia and Cricket NSW. You will also have the opportunity to request a detailed report of your child/dependent's individual results. If there is anything you feel unsure about or would like to be informed of the aggregate research findings, we encourage you to contact Rebecca Dennis on 0402 798 755 or Professor Caroline Finch on 02 9385 5361.

Yours sincerely,



Ms Rebecca Dennis

THE UNIVERSITY OF NEW SOUTH WALES, CRICKET AUSTRALIA and CRICKET NSW

PARTICIPANT INFORMATION STATEMENT AND CONSENT FORM (continued)

Cricket Fast Bowling Workload, Injury and Performance Project

You are making a decision whether or not to allow your child/dependent to participate. Your signature indicates that, having read the Parental (and Guardian) Information Statement, you have decided to allow your child/dependent to take part in the study.

…………………………………………………… Signature of Parent/Guardian of Research Participant	…………………………………………………… Signature of Witness
…………………………………………………… (Please PRINT name of Parent/Guardian)	…………………………………………………… (Please PRINT name of witness)
…………………………………………………… Signature of Research Participant	…………………………………………………… Nature of Witness

……………………………………………………
(Please PRINT name of Research Participant)

……………………………………………………
Date

……………………………………………………
Signature(s) of Investigator(s)

……………………………………………………
(Please PRINT Name of Investigator)

THE UNIVERSITY OF NEW SOUTH WALES, CRICKET AUSTRALIA and CRICKET NSW

PARTICIPANT INFORMATION STATEMENT AND CONSENT FORM (continued)

REVOCATION OF CONSENT

Cricket Fast Bowling Workload, Injury and Performance Project

I hereby wish to **WITHDRAW** my consent for my child/dependent to participate in the research proposal described above and understand that such withdrawal **WILL NOT** jeopardise any treatment or my child/dependent's relationship with The University of New South Wales, Cricket Australia or Cricket NSW.

…………………………………………………… ……………………………………………………….
Signature of Parent/Guardian of Research Participant Date

……………………………………………………
(Please PRINT Name of Parent/Guardian)

……………………………………………………
Signature of Research Participant

……………………………………………………
(Please PRINT Name of Research Participant)

The section for Revocation of Consent should be forwarded to the following address:

Professor Caroline Finch
NSW Injury Risk Management Research Centre
The University of New South Wales
Sydney 2052.

Appendix 11 Approval for the study presented in Chapter B3

THE UNIVERSITY OF
NEW SOUTH WALES

HUMAN RESEARCH ETHICS
COMMITTEE (HREC)

24 July 2003

Dr Andrew McIntosh
School of Safety Science

Dear Dr McIntosh

Cricket fast bowling workload, injury and performance project
(HREC 03168)

At its meeting held on 15 July 2003, the Human Research Ethics Committee (HREC) considered the above project.

Exercising the authority delegated to me by the Vice-Chancellor, I give permission for this project to proceed.

Would you please note:-

- approval is valid for five years
- any modifications to the project must have the prior written approval of the Committee
- Consent Forms are to be retained within the archives of the School and made available to the Committee upon request.

Would you please note that it is the Committee's principle that if the project includes participants under 14 years of age, parents/guardians (rather than participants) should provide you with written consent (children under 14 years of age *may* sign the Consent Form if they wish). Furthermore, if the project includes participants in the age group of 14 – 16 years, then *both* participants and their parents/guardians should provide you with written consent. If the project includes participants over 16 years of age, it is sufficient to obtain written consent only from these participants. Please replace The wording "...to participate in this important research project" with "...to participate in this research project" (Information Statement, page 1 of 4 refers). Given that Professor Bruce Elliott is an employee of the University of Western Australia, the approval should be forwarded to the IEC of that University for ratification.

Would you please forward your response to the above and the amended Information Statement (with changes bolded or underlined) to Mrs Margaret Wright, Ethics Secretariat, UNSW.

Yours sincerely

A M Lloyd

Professor Andrew Lloyd
Presiding Member
HREC

UNSW SYDNEY NSW 2052
A U S T R A L I A
Telephone: +61 (2) 9385 [illegible]
Facsimile: +61 (2) 9385 [illegible]
Email: ethics.sec@unsw.edu.au
Location: Rupert Myers Building
Research Office / Ethics,
Gate 14, Barker Street Kensington
ABN [illegible]

Appendix 12 Musculoskeletal screening procedures manual for the study presented in section B3

Fast Bowling Workload, Injury and Performance Project
2003-2004

Musculoskeletal screening manual

September 2003

Screening Test Procedures

This section describes each of the tests to be used in the physiotherapy assessment for the Fast Bowling Workload, Injury and Performance Project. All tests were outlined by Harvey and colleagues (1998), unless otherwise specified.

Recording measurements

For each player, the results of each of the screening tests must be recorded on the datasheet provided. The musculoskeletal tests must be performed in the order defined on the datasheet and all tests need to be performed on all subjects.

Athletes should be tested whilst lying on a standard physiotherapy bench, unless otherwise specified. All measurements recorded by a tape measure must be read to the nearest 0.1cm (unless otherwise specified in the test protocol) whilst goniometric measurements will be recorded to the nearest degree. Where tests are undertaken for both sides of the body, the **left side is to be measured first**. If the athlete complains of pain during any of the tests, please record this in the comments section of the datasheet.

Stabilisation

Accurate measurement of the joint range of motion requires stabilisation of the proximal bony segment of the joint being measured. Without adequate stabilisation to isolate the intended motion, the athlete may substitute motion at another joint for the motion requested. Lack of sufficient stabilisation may also affect the reliability of the measurements taken (Berryman Reese & Bandy, 2002).

Instructing the athlete

The athletes should be provided with thorough instructions prior to performing any of the tests. Describe exactly what will be taking place and why the measurement is being performed. Measurement of range of motion and muscle length, particularly active motion, requires the full cooperation of the athlete. As the athlete's understanding of the procedure increases, so does the likelihood that athlete will provide his best effort during the assessment.

Once the athlete is positioned and stabilised, the examiner should move the joint passively through the available range of motion. Firstly, this makes the athlete aware of the movement and will then be able to cooperate more fully and accurately with the procedure. Secondly, the physiotherapist will also be able to make a rough assessment of the athlete's available range of motion and confirm this with the goniometric measurement (Berryman Reese & Bandy, 2002).

1. Knee extension (90/90)

Purpose: To assess hamstring length and range of assisted active knee extension in a position of hip flexion

Landmarks: Inferior border of lateral malleolus and head of fibula

Protocol:

1. Athlete lies supine, head resting on table (no pillow), arms crossed on chest
2. Passively flex hip of testing leg until thigh is vertical (use spirit level to align)
3. This position is maintained throughout the test by support behind the posterior thigh
4. Maintain opposite leg in fully extended position throughout the test by “pushing” heel away from body
5. Keep foot relaxed and ask athlete to straighten knee until thigh begins to move from vertical position
6. Support the athlete behind the thigh and calf of the testing leg to the point of onset of resistance, but do not push the athlete beyond R1
7. It is important to note that in cases in which full knee extension is achieved without thigh movement, the knee is flexed while the thigh is moved to 30° past the vertical position (ie. 120° hip flexion). With a relaxed foot, the knee is again straightened until the thigh begins to move.

Record: The angle from complete knee extension at which the thigh begins to move is recorded by aligning the goniometer with the landmarks described above and the vertical plane. Flexion values are recorded as negative. In cases in which the hip is further flexed to 120° flexion, the measurement is recorded as 120 – x, where x = angle of knee extension deficit (Harvey et al., 1998).

2. Modified Thomas Test

Purpose: To assess the flexibility of the hip flexors (iliopsoas predominantly) and TFL/ITB

Landmarks: Both ASIS, greater trochanters, point bisecting the superior border of the patella, knee joint line laterally between the lateral femoral condyle and fibula head

Protocol:

Iliopsoas

1. The athlete sits perched on the end of a plinth and rolls back to lying with both knees held to the chest (this ensures that the lumbar spine is flat on the plinth and the pelvis is in posterior rotation)

2. The athlete holds the contralateral hip in maximal flexion with the arms while the tested limb is lowered towards the floor
3. The athlete is asked to relax the hip and thigh muscles, so a passive test end point position is obtained due to gravity alone
4. The angle of hip flexion is measured with the athlete in the test position
5. The goniometer is centred over the greater trochanter, with the fixed axis directed vertically using the spirit level. This allows measurements relative to the horizontal plane
6. The mobile arm is pointed toward the lateral knee joint line, representing the line of the femur

Record: The hip angle is recorded relative to the horizontal, or 0° axis, as a positive or negative angle. ie. 7° represents a hip flexed above the horizontal; -12° represents a hip that is below the horizontal

ITB/TFL

1. The athlete sits perched on the end of a plinth and rolls back to lying with both knees held to the chest (this ensures that the lumbar spine is flat on the plinth and the pelvis is in posterior rotation)
2. The athlete holds the contralateral hip in maximal flexion with the arms while the tested limb is lowered towards the floor
3. The contralateral hip is maintained in maximal flexion and external rotation is added in order to move the ASIS's into a parallel alignment
4. Hip abduction angle is measured with the centre of the goniometer over the ipsilateral ASIS
5. The flexible arm is positioned to the opposite ASIS
6. This procedure measures the 'real', not apparent angle of hip abduction

Record: The angle of hip abduction is measured, with the line perpendicular to that of the ASIS considered as 0° (can be found on goniometer scales). A positive angle represents hip abduction.

3. Prone hip internal/external rotation in neutral

Purpose: To assess ranges of passive hip rotation in neutral hip position

Landmarks: Inferior pole of patella, tibial tuberosity

Protocol:

Internal rotation

1. Lay prone with knees bent to 90°, chin resting on plinth, arms by sides
2. Let ankles move away from each other as far as possible passively (gravity assists), ensuring hip does not flex

External rotation

1. Lay prone with one knee bent to 90°, chin resting on plinth, arms by sides. Keep knees together and ASIS on plinth throughout test
2. Let ankle drop towards opposite side as far as possible

Record: Angle formed by the line of the tibia relative to vertical in each position (Harvey et al., 1998).

4. Combined elevation test

Purpose: To assess thoracic extension (strength/ROM), shoulder girdle flexion and scapula retraction

Landmarks: Lateral border of ulnar styloid process

Protocol:
1. Lay prone with chin on plinth, both arms outstretched in front of athlete
2. Keep feet, hips, chest and chin on plinth throughout test
3. Actively extend elbows and lock thumbs together, palms towards floor
4. Raise arms off floor as high as possible

Record: Using a tape measure, record the distance (in centimetres) from the plinth to the bottom of the thumbs (Harvey et al., 1998).

5. Prone four point hold

Purpose: To assess lower abdominal strength and endurance

Landmarks: NA

Protocol:
1. Lay prone on towel on floor, resting on forearms, feet in a push-up position
2. Keep hands held shoulder width apart throughout the test, do not allow athlete to grip hands together
3. Pull belly button in towards spine and hold
4. Raise trunk off the floor and hold neutral lumbopelvic position until either (a) the athlete experiences lower back pain or (b) the athlete can no longer hold the position correctly

Record: Using a stopwatch, record the number of seconds the athlete can hold the position.

6. Bridging hold

Purpose: To assess gluteal strength and endurance

Landmarks: NA

Protocol:

1. Lay supine on plinth, with knees bent at 90°
2. Raise one foot off the bed and fully extend knee with foot in a neutral position
3. Pull navel to spine and maintain straight alignment from shoulder to hip through to knee
4. Try not to dig heel into the plinth and keep hamstrings relaxed
5. Use gluteal muscles to keep hips up and stop low back from arching
6. Hold for as long as possible until either (a) the athlete cannot hold this position correctly, (b) the athlete experiences lower back pain, (c) the athlete experiences cramping in the hamstring muscles of the foot on the plinth

Record: Using a stopwatch, record the number of seconds the athlete can hold the position on each leg.

7. Ankle dorsiflexion lunge

Purpose: To assess range of talocrural dorsiflexion in a functional position for weight bearing sports

Landmarks: Nil

Protocol:

1. The tape measure is fixed along the floor with the 0cm point at the junction of the floor and wall
2. The player positions their foot on the tape on the floor so that the heel line and big toe are aligned on the tape measure
3. The physiotherapist holds the player's heel to prevent it from lifting off the floor and subtalar joint should remain in neutral throughout the test
4. The player lunges forward until their knee touches the wall. Up to five attempts can be made to find the maximum distance from the wall where the subject can touch their knee to the wall without their heel lifting from the floor

Record: At the maximum lunge point, the distance from the big toe to the wall is recorded from the tape measure to the nearest 0.5cm (Harvey et al., 1998).

8. Calf heel raises

Purpose: To assess endurance of ankle plantarflexor muscles in a weightbearing task

Landmarks: Nil

Protocol:

1. Athlete standing with balls of feet on edge of step, heels off step

2. Athlete is instructed to stand on one foot and to rise onto ball of foot as high as possible, then slowly lower heel as low as possible. Knee must be kept extended throughout movement
3. Heel raise/lower cycle is repeated continuously (without a rest) until the athlete is unable to raise through full range with the knee extended. Athlete is to perform heel raises at a rate of approximately one cycle/second

Record: Examiner counts heel raise/lower cycles completed on each leg (Harvey et al., 1998).

References

1. Berryman Reese, N., Bandy, W.D. 2002, Joint range of motion and muscle length testing, W.B. Saunders, Sydney.

2. Harvey, D., Mansfield, C., Grant, M. Screening test protocols: Pre-participation screening of athletes, Australian Sports Commission, Canberra.

Recording sheet

Name: **Date of screening:**

Current injuries:

Injury history:

Standing height (with shoes) _________ cm Weight (without shoes) _________ kg
Standing height (without shoes) _________ cm Chest girth (no shirt) _________ cm

	TEST	LEFT SIDE	RIGHT SIDE
1 *	Passive knee extension (90/90)		
2a *	Modified Thomas Test - hip extension angle		
2b *	Modified Thomas Test - hip abduction angle		
3a *	Hip internal rotation in neutral (prone)		
3b *	Hip external rotation in neutral (prone)		
4 ◆	Combined elevation test		SINGLE MEASUREMENT
5 ^	Prone 4 point hold		SINGLE MEASUREMENT
6 ^	Bridging hold		
7 ◆	Ankle dorsiflexion lunge (subtalar neutral)		
8 #	One legged calf heel raises		

Note: * measured with goniometer to nearest degree ^ measured to nearest second
◆ measured to nearest 0.1cm # number to failure

Appendix 13 Technique screening procedures manual for the study presented in section B3

Fast Bowling Workload, Injury and Performance Project
2003-2004

Fast bowling technique analysis manual

September 2003

One of the major components of the National Pace Bowling Program is the continuing assessment of fast bowlers, including analysis of technique using the siliconCOACH software. This section describes the procedures to be followed for the fast bowling technique analysis in completing the reporting requirements of the National Pace Bowling Program. For the 2003-04 season, a research project will also be conducted which examines the role of fast bowling technique in the outcomes of injury and performance with fast bowlers aged 12 years and over and will use the information recorded in this technique analysis.

The siliconCOACH Fast Bowling Template incorporates various biomechanical and technical measurements of the fast bowling action. These measurements are designed to provide feedback for coaches, players and sports scientists in an effort to reduce the risk of injury and to enhance performance. The information can also be assessed in conjunction with workload, physiotherapy screening and fitness testing data to determine appropriate parameters to reduce the risk of injury as well as to optimise fast bowling performance.

The tests chosen for the two dimensional multiple plane analysis of bowling technique and the procedures used are described below.

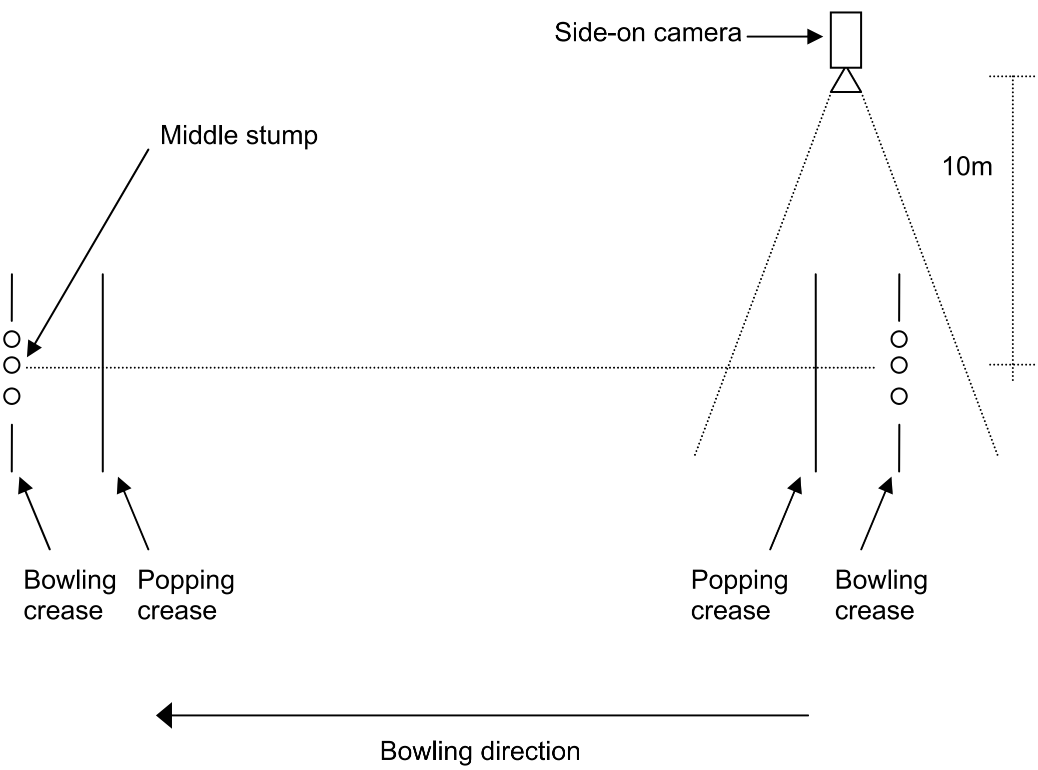
1. Camera preparation

The siliconCOACH fast bowling analysis requires side-on and overhead digital cameras, as distributed by Cricket Australia. You may also use a front on camera, however, this is not required for the standard National Pace Bowling Program analysis of technique. Please refer to the diagram below for the appropriate camera set-up.

Cameras should be set from the bowling crease at the distances outlined below and should be fully zoomed in. This reduces the depth of field of the image, therefore reducing perspective error. The focus for both the side-on and overhead camera should be centred halfway between the popping and bowling creases. The background should be as plain and uncluttered as possible. Where possible, filming should be conducted outdoors in the early afternoon to ensure as much natural daylight as possible. When using indoor facilities, lights should be set as bright as possible to ensure the shutter speed of the camera will operate as fast as possible.

a) Side-on camera set up

Where possible, the camera should be set up 10m away from the bowling crease, perpendicular to the bowling direction and on the bowling side of the body (eg. for a right-handed bowler, the camera should be on the right side of the bowler as they are bowling). The camera should be set up perpendicular to the line joining the middle to middle stump. Please mount the camera on a tripod, set it level and keep it still, as panning shots will interfere with calculating the measures of speed. Focus the camera halfway between the popping crease and the bowling crease, with the background as plain and uncluttered as possible. The height of the camera should be approximately equal to the height of the bowler's centre of mass (approximately just below the navel). This is to ensure that measurements of height and length are not distorted by the camera angle.



Side-on camera set up for analysis of bowling technique

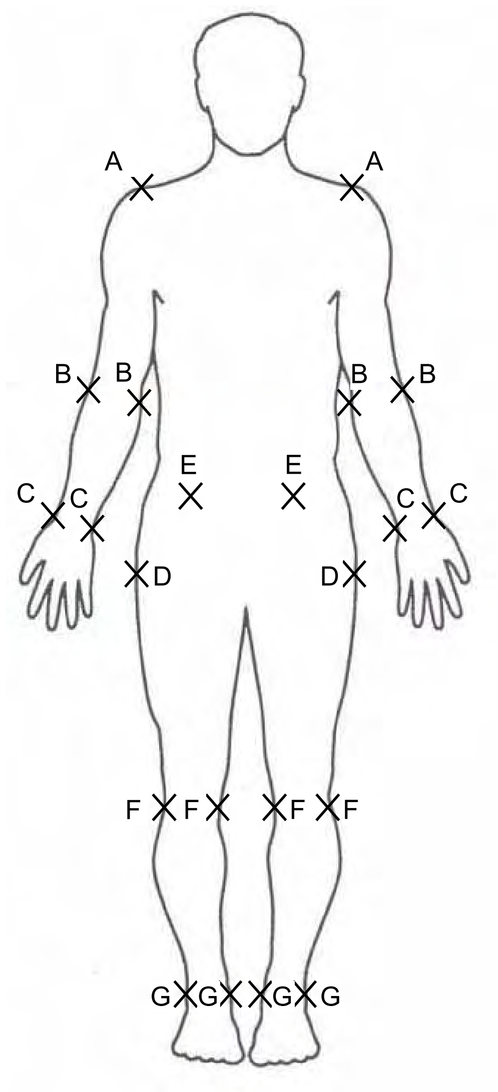
b) Overhead camera set up

The overhead camera should be 4m above the ground, directly above the bowling crease and focussed halfway between the popping crease and the bowling crease. The camera should be mounted on a stand, perpendicular to the floor and kept still.

2. Bowler preparation

To ensure that the measurements calculated in siliconCOACH are as accurate as possible, bowlers should be instructed to wear bike pants or tights only, along with their usual training shoes. The following sites (as shown in the attached diagram) should be marked by a physiotherapist using tape and/or a non-permanent black marker to allow digitisation in siliconCOACH:

- A - acromion processes (shoulder)
- B - medial and lateral humeral epicondyle (elbow)
- C - ulnar and radial styloid (wrist)
- D - greater trochanter (side of hip)
- E - anterior superior iliac spine (ASIS - front of hip)
- F - medial and lateral femoral epicondyle (knee)
- G - medial and lateral malleolus (ankle)



Sites of body markers for analysis of bowling technique

3. Video capture

The bowlers should warm up and be ready to bowl at full match pace. They should be asked to bowl a minimum of four legal deliveries (front foot no-ball law) over the wicket whilst being filmed. For the purposes of standardised analysis, instruct the bowler to attempt to bowl a good line and length.

4. Analysis of video footage using the siliconCOACH software

For the analysis of video footage, it is preferable that a single delivery is analysed from both the side-on and overhead views, as opposed to analysing separate deliveries for each view. To enable this, a mixer or the dual capture facility available on some computers should be used when capturing the footage from the side-on and overhead cameras.

a) Setting the scale for measurements

When using the measurement tools in siliconCOACH to determine distance and speed in the analysis of the footage recorded by the side-on camera, use the distance between the bowling and popping creases (1.22m) to set the measurement scale.

b) Determining back foot impact and front foot impact

Back foot impact (BFI) and front foot impact (FFI) are determined by the point in time when the foot was in first full contact with the ground. If the heel does not contact the ground during the back foot landing, BFI is defined as the frame that the movement of the foot about the toe has completed. If the movement of the foot about the toe continues throughout the back foot landing, BFI is defined as the frame when the foot is most stable and bearing the greatest load, prior to the bowler pushing off the toe of the back foot. This may require the footage to be played backwards and forwards a few times to allow the judgment of BFI and FFI to be made. An important aspect of the Fast Bowling Workload, Injury and Performance research project is to assess the reliability of the procedures currently used to assess fast bowling technique. To enable this assessment to be made, it is vital to review the frames chosen by each coach/analyst for BFI and FFI. This can be done by using the stopwatch function in siliconCOACH to record the time of the frames you have used for BFI and FFI. Please also record and save the images of BFI and FFI using the ReportPak module in siliconCOACH.

When determining the frame of BFI and FFI in the footage recorded by the overhead camera, synchronised footage from the side-on camera should be used to allow the feet to be seen more clearly.

c) Stride length

Using footage recorded by the side-on camera, use the discrete measurement tool to measure the length of the stride from the back of the heel of the back foot at BFI to the back of the heel of the front foot at FFI, to the nearest centimetre.

A normalised stride length will be automatically calculated in siliconCOACH, using the standing height of the bowler as measured in the fitness and anthropometric assessment. Stride length should be expressed as a percentage of the standing height of the bowler, recorded to the nearest percent.

d) Front knee angle

Use footage recorded by the side-on camera. Use the normal angle tool to calculate the angle of the front knee at FFI, using the line formed by the medial malleolus marker, medial femoral epicondyle marker and up the middle of the thigh. Record this angle again in the frame in which the front knee is most flexed after FFI and prior to, or at, the frame of ball release. The angle of the front knee at FFI and the maximum angle of the front knee between FFI and ball release should be recorded to the nearest degree.

e) Height of ball release

Again using the side-on footage, with the horizontal line tool, draw a line directly underneath the front foot in the frame at ball release. Use the vertical line tool to draw a straight line from the ball to the horizontal line you have just drawn. Then use the discrete measurement tool to calculate the distance from the ground to the centre of the ball, to the nearest centimetre.

A normalised height of ball release will be automatically calculated using the standing height of the bowler, as measured in the fitness and anthropometric testing. The height of ball release should be expressed as a percentage of the standing height, to the nearest percent.

f) Ball speed

With footage recorded by the side-on camera, use the continuous measurement tool to calculate ball speed from the frame at ball release (the first frame the ball is not in contact with the hand) to one frame after ball release, to the nearest km/h.

g) Shoulder angle at BFI

When using footage from the overhead camera, it is vital to use a synchronised side-on view to determine BFI and FFI. Shoulder counter rotation has been recognised as one of the most significant risk factors for injury and therefore it is vital that it is calculated correctly. As BFI and FFI are very difficult to assess using the overhead footage only, it is essential that the synchronised side-on footage is used.

Using footage recorded by the overhead camera, and the acromion process body markers as a guide, draw a line through the primary alignment of the shoulders at the frame of BFI. This line should be continued down the pitch, parallel to the alignment of the pitch. The angle of the shoulders, relative to the pitch alignment in the direction of bowling, should then be recorded to the nearest degree.

h) Minimum shoulder angle

Using footage recorded by the overhead camera, use the blend tool to freeze the shoulders at BFI and advance the footage frame by frame. Determine the frame in which the shoulders obtain the most side-on position between BFI and ball release (usually just before FFI, or sometimes at FFI). As with shoulder angle at BFI, the angle of the shoulders, relative to the pitch alignment in the direction of bowling, should be recorded to the nearest degree.

i) Shoulder counter-rotation

This parameter is automatically determined by subtracting the minimum shoulder angle from the shoulder angle at BFI. This measures how much the bowler rotates their shoulders to a more side-on position after BFI, to the nearest degree.

Appendix 14 Fitness testing procedures manual for the study presented in section B3

Fast Bowling Workload, Injury and Performance Project
2003-2004

Fitness testing manual

September 2003

Bowlers should be asked to wear their normal training clothes and comfortable running shoes. Prior to testing, they should complete a warm up consisting of a short run and stretching. The tests described below should be conducted in the order in which the tests are listed.

1. Height

A tape measure was fixed to a vertical wall. The barefoot bowler should stand erect with their heels together and arms hanging naturally by their sides. The heels, buttocks, upper part of the back and back of the head should be in contact with the wall, with the weight evenly distributed on both feet. The bowler should be instructed to look straight ahead and take a deep breath. Then place a set square at the most superior aspect of the head, in contact with the tape on the wall. Ask the bowler to then step away from the wall and record the height of the bowler to the nearest 0.1cm.

2. Body mass

The body mass of bowlers should be assessed using electronic digital scales. The scales should be placed on a hard, level surface and bowlers assessed while wearing shorts only. Bowlers should be instructed to stand on the scales without support, with weight evenly distributed on both feet. Measure mass to the nearest 0.1kg.

3. Skinfolds

Prior to skinfold assessment, identify and mark the landmarks listed below. Landmarks are identifiable skeletal points found by palpation that generally lie close to the body's surface and are the "markers" for identifying the exact location of the measurement site:

- Acromiale – the point at the most lateral, superior border of the acromion process and which is midway between the anterior and posterior borders of the deltoid muscle when viewed from the side.

- Radiale – The point at the most superior lateral border of the head of the radius.

- Mid-acromiale-radiale – The point equidistant from acromiale and radiale. This point is projected to the posterior and anterior surfaces of the arm as a horizontal line.

- Subscapulare – The undermost tip of the inferior angle of the scapula.

- Iliospinale – The most inferior aspect of the anterior superior iliac spine.

Once the landmarks are identified, skinfolds should be assessed using Harpenden calipers, with all measurements taken on the right side of the body and recorded to the nearest 0.1mm.

a) Triceps

Raise the skinfold on the marked posterior mid-acromiale-radiale line. The fold should be parallel to the line of the upper arm.

b) Biceps

Raise the skinfold on the marked anterior mid-acromiale-radiale line. The fold should be parallel to the line of the upper arm.

c) Subscapular

This skinfold should be raised at the marked site 2cm along a line running laterally and obliquely downward from the subscapulare landmark at an approximate 45° angle as determined by the natural fold lines of the skin.

d) Supraspinale

This fold should be raised at the point where the line from the iliospinale landmark to the anterior axillary border intersects at the horizontal level of the superior border of the ilium. The fold runs medially downward at about a 45° angle.

e) Abdominal

This is a vertical fold raised 5cm from the right side of the omphalion (midpoint of the navel).

f) Front thigh

The bowler's knee should be bent at 90° by placing their foot on a box. The site should be marked parallel to the long axis of the femur at the midpoint of the distance between the inguinal fold and the superior border of the patella.

g) Medial calf

The bowler should be asked to stand with their foot on a box, with their knee bent at 90° and calf relaxed. A vertical fold should be raised on the medial aspect of the calf at a level where it has maximal circumference.

The measurements for these sites should be added together to determine the sum of seven skinfolds.

4. Vertical jump

The bowler must stand straight, wearing training shoes, with feet flat on the floor and extend their bowling arm and fingers fully to reach as high as possible on a yardstick vertical jump device (vertec). The vertec device consists of a stand with a number of movable vanes that indicate the jump height. The bowlers knock the plastic vertec fingers and the number of the vertec fingers left in place was recorded as their starting height. The bowler then performs a countermovement jump by bending down at the knees before immediately driving upwards using both arms. They should not be permitted to complete any preliminary steps or shuffling. As they perform the countermovement jump, they should stretch out their bowling hand and knock the plastic vertec fingers. The highest jump from 3 trials, with a rest period of 10 – 15 seconds between trials, should be recorded. The starting height is subtracted from the peak height to determine the height jumped in centimetres.

5. Overhead medicine ball throw

The overhead medicine ball throw should be conducted in a similar fashion to a soccer throw in. The bowler should stand on a grass surface, wearing training shoes with their feet shoulder width apart. Holding a 3kg medicine ball directly above their head with elbows bent slightly, they then take one step forward, whilst lowering the medicine ball back behind their head. They then should extend the elbows, brought the ball over their head and throw the ball out in front of them as far as possible. Advise the bowler to release the ball at an angle of approximately 35°. Both feet must stay grounded at ball release. After they have released the ball, the front foot should stay planted, but the bowler is allowed to take one step forward with their back foot to meet the front foot as a follow through. A countermovement swing prior to the throw (ie. attempting to gain momentum by bringing the ball down in front of the chest prior to drawing it back over the head) should not be permitted. A tape measure should be placed along the ground with the front edge of the bowler's front foot on 0cm. The distance for each throw should be measured to the middle of the ball bounce. The best of three attempts, to the nearest 5cm, is recorded.

6. Chest medicine ball throw

The bowler should sit on a grass surface with their back against a wall, legs extended in front of them, knees straight, with hips bent at 90°. They hold a 3kg medicine ball with both hands against their chest, with elbows bent. They then extend their elbows and push the ball directly out in front of them as far as possible using both hands. They should be advised to throw the ball at an angle of approximately 45°, starting from their chest, not from the stomach upwards. A countermovement swing is not permitted (ie. extending elbows in front of them, then drawing the ball into the chest before throwing). They should also not be permitted to throw the ball using one hand. A tape measure should be placed along the ground starting at the base of the wall. The distance to the middle of the ball bounce is measured. The distance for the best of three attempts, to the nearest 5cm, is recorded.

7. Side-on medicine ball throw

The bowler stands with their feet shoulder width apart, feet facing perpendicular to the direction of the throw. For a right-handed bowler, the left foot is the leading foot. For a left-handed bowler, the right foot is the leading foot. The bowler should hold the ball in both hands directly in front of their body at hip height, with arms outstretched. They then bend the knees slightly and swing the ball backwards, keeping the arms straight. They then swing the ball back in front of them and release to the side as far as possible (the movement is similar to a golf swing). The bowler's arms should remain outstretched throughout the throw and both feet should remain grounded throughout the throw. They can be advised to throw the ball at an angle of approximately 45°. On ball release, the bowler is permitted to pivot the back foot about the toe, but not to lift it off the ground. A tape measure is placed along the ground, with the front edge of the bowler's leading foot on 0cm. The distance from the start of the tape to the middle of the ball bounce is measured. The distance for the best of three attempts, to the nearest 5cm, should be recorded.

8. 40 metre sprint

This test is to be conducted on a dry, short mown grass surface, with bowlers wearing their spiked cricket shoes. The running lane should be set up so that the bowlers are running perpendicular to the direction of any wind. Electronic timing light gates should be placed at the start line and at 40m. Reflectors are placed directly opposite timing gates at a distance of 2m. The bowler then stands with the toe of their preferred front foot up to the start line. The bowler should be instructed to hold the start position (ie. no rocking back and forth) before the start. The tester then gives the instructions "ready, set, go", with the bowler starting to run on "go". The bowler should be told to run as fast as possible and not stop until after they have run past the last timing gate at 40m. Electronic timing light gates record the start time and the finish time at 40m. The bowler should complete two trials approximately 5 minutes apart, with the times recorded for both attempts to the nearest 1/100 of a second.

9. Yo-yo intermittent recovery test

This test is being used in place of the traditionally used “beep test”. Two markers should be positioned exactly 20m apart from each other. A third marker should also be positioned 5m behind and slightly to the side of the start marker. An audio cassette, provided with the testing material, is used to give instructions to those completing the test as well as to emit signals to control the timing of the test. After listening to the instructions on the audio tape, the bowler runs forward 20m at the time of the first signal. The bowler should be instructed to adjust their running speed so that they reach the 20m marker exactly at the time of the next signal. A turn is made at the 20m marker and the bowler should then run back to the first marker. After the start marker is passed, the bowler continues forward at a lower tempo, runs around the cone 5m away and returns to the start marker, where they wait for the next signal. The time allowed for this jog around the 5m marker is 10 seconds.

As the test progresses, the time at which the bowler needs to run the 20m shuttle progressively increases as controlled by the audio tape (ie. the time between the signals is shortened). With all participants, Level 1 of the Intermittent Recovery Test should be used.

The course should be repeated until the bowler is unable to maintain the indicated speed for two trials. The first time the marker is not reached a warning is given and the next time, the bowler is instructed to stop. The speed level at which the bowler withdraws from the test, as well as the total number of metres completed should be recorded.

Appendix 15 Bowling workload logbook for the study presented in Chapter B3

Fast Bowling Workload, Injury and Performance Project

Weekly bowling workload recording sheet

Name: ________________________ DOB: ____/____/______

KEY:	Surface:		Intensity:	
		T = turf		H = high (full run-up, match intensity)
		S = synthetic		M = medium (shorter run-up, controlled pace)
		I = indoor		L = low (short/no run-up, technique work)

TRAINING: (one row per training session)

DETAILS					COMMENTS
Date	Squad / Team	Surface (T, S, I)	Intensity (H, M, L)	Balls Bowled	(eg injuries, conditions, general feeling etc)

MATCHES: (one row per match day)

DETAILS					COMMENTS
Date	Team	Surface (T, S, I)	Warm-up balls	Full Statistics (O-M-R-W-Extras)	(eg injuries, conditions, general feeling etc)

Appendix 16 Letter from Brett Lee to all bowlers participating in the study presented in Chapter B3

CRICKET AUSTRALIA

11 November 2003

Dear Fellow Fast Bowler,

I am writing to you about the research project looking at fast bowling workload and its relationship to injury, being conducted by Cricket Australia and the University of New South Wales. The researchers involved in this project are looking to develop guidelines to help reduce the risk of injury to fast bowlers.

As you know, part of your involvement in the project requires you to count the number of balls you bowl during each training session and match, complete a bowling workload diary and submit this to the researchers each week. Whilst this may seem a time consuming and boring task, I encourage you to do this as I feel it is worthwhile for a number of reasons.

Firstly, whilst guidelines exist for fast bowlers' workloads in matches and training, fast bowlers are still getting injured. The more information that can be gathered will help researchers propose more accurate guidelines for workloads based on evidence and this can help to reduce the risk of injury.

Secondly, it is thought that young fast bowlers are more prone to suffering from overuse type injuries. I experienced two episodes of stress fractures to my lower back, the first when I was 17 and the second when I was 20. If I had monitored my workload more closely in the years leading up to these injuries, I feel my risk of getting injured would have been significantly reduced.

Lastly and very importantly, if you are going to achieve your maximum potential as a fast bowler, you need to take responsibility for looking after the factors that will help prevent injury. These include appropriate strength and flexibility training, monitoring your technique and recording your bowling workload. After my second lower back stress fracture, I took the responsibility for looking after these factors and I believe that doing that has been vital to my participation in cricket at the top level. I encourage you to take this responsibility also and give yourself the best opportunity to achieve your potential in cricket.

Thanks for taking the time to read this letter and good luck for the rest of the season.

Best wishes,

Brett Lee