EXERCISE-BASED INJURY PREVENTION FOR COMMUNITY-LEVEL ADOLESCENT PACE BOWLERS

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Author Declaration

I declare that:

  a) The thesis is my own account of my research, except where other sources are acknowledged.

  b) The extent to which the work of others has been used is clearly stated in each chapter and certified by my supervisors.

  c) The thesis contains as its main content, work that has not been previously submitted for a degree at any other university.

Mitchell Robert Loaring Forrest

A note on formatting and style

This thesis has been developed in the format of Thesis by Publication. The formatting of Chapters 2-5, which have been published in scientific journals, may therefore differ slightly. It is hoped that the final amalgamation allows for the development of a cohesive body of research that can be easily followed. The PhD thesis has continuous pagination, which can be seen at the bottom right of each page.

Statement of Contribution of Others

The published/submitted chapters represent collaborative works; however, the PhD candidate for which this thesis represents has completed the majority of the study design, data collection, data analyses, interpretation, and drafting of the manuscript.

Contribution to each chapter

Chapter 2: *Risk factors for non-contact injury in adolescent cricket pace bowlers: a systematic review*

Name	Design	Data collection	Data analysis	Interpretation	Manuscript development
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Jeffrey Hebert	20%	5%	10%	10%	10%
Stefano Brini	0%	15%	5%	0%	2.5%

I confirm that the level of contribution attributed to me is correct.

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Chapter 5*: Modifying bowling kinematics in cricket pace bowlers with exercise-based injury prevention: a cluster-randomised controlled trial*

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Thesis Abstract

Sporting injuries are on the rise and wide-scale injury prevention strategies are needed in community-level sport. Research indicates that community-level adolescent pace bowlers could benefit from exercise-based injury prevention programs (IPPs), however, a specific program for this group has not been developed. The primary aim of this thesis was to therefore develop a specific IPP for community-level adolescent pace bowlers and investigate if this program could modify risk factors for injury in this population.

The Translating Research into Injury Prevention Practice (TRIPP) framework guided the progression of studies in this thesis. In Chapter 2, risk factors for injury in adolescent pace bowlers were systematically reviewed. The review included all experimental and observational studies that reported risk factors for non-contact injuries in pace bowlers aged 12-19 years. The Newcastle-Ottawa Quality Assessment Scale was used to assess risk of bias. In Chapter 3 the various barriers and facilitators to program implementation at the community-level were identified and used to guide the development of an IPP that was appropriate for community-level adolescent pace bowlers. In Chapters 4 and 5 a cluster-randomised controlled trial was employed to examine the efficacy of this IPP to modify neuromuscular risk factors and alter bowling kinematics. Eligible pace bowlers from eight cricket organisations (clusters) were recruited and then randomised into either an intervention group or control group. The intervention group completed an eight-week IPP while the control continued their normal cricket activity. Either side of the eight-week intervention period all participants attend a baseline and follow-up session where measures of muscle strength, muscle endurance, dynamic neuromuscular control and bowling kinematics were assessed. The treatment effect of the IPP was estimated with linear mixed models.

Chapter 2 identified several potentially modifiable risk factors for injury in adolescent pace bowlers and these included; excessive lateral trunk flexion while bowling, kinematics of

pelvis and hip while bowling, reduced trunk endurance, and poor lumbo-pelvic-hip movement control. There were conflicting results amongst the studies which investigated the mixed technique, bowling workload, and quadratus lumborum asymmetry. Among the five cross-sectional studies, risk of bias was high and very high. Of the 11 cohort studies, three were rated as low risk of bias and eight as high risk of bias. With the information gathered in Chapter 2, an exercise program to modify risk factors was developed in Chapter 3. The program included exercises to improve; eccentric strength of the external shoulder rotators, hip adductor strength, eccentric hamstring strength, dynamic neuromuscular control of the lumbo-pelvic region and lower-limbs, and trunk extensor endurance. Chapter 3 also considered the various facilitators to program implementation at the community-level, and therefore included exercises that were; simple to learn, non-reliant on expensive equipment, and time-efficient. In Chapter 4 the efficacy of this newly developed IPP to modify neuromuscular risk factors was assessed. There were significant treatment effects (estimated marginal mean with 95% confidence intervals) favouring the intervention group for; isokinetic shoulder strength (90°/s) (0.05 Newton meters per kilogram (N.m/kg); 0.02 to 0.09), isokinetic hamstring strength (60°/s) (0.32 N.m/kg; 0.13 to 0.50), hip adductor strength dominant side (0.40 N.m/kg; 0.26 to 0.55) and non-dominant side (0.33 N.m/kg; 0.20 to 0.47), Star Excursion Balance Test reach distance dominant side (3.80 percent of leg length (%LL); 1.63 to 6.04) and non-dominant side (3.60 %LL; 1.43 to 5.78), and back endurance (20.4 seconds; 4.80 to 36.0). No differences were observed for isokinetic shoulder strength (180°/s) (p=0.09), isokinetic hamstring strength (180°/s) (p=0.07), lumbo-pelvic stability (p=0.90), and single leg squat knee valgus angle (dominant p=0.06, non-dominant p=0.15). In Chapter 5 there were significant treatment effects favouring the intervention group for shoulder counter-rotation (-3.75°; -7.19 to -0.32) and lateral trunk flexion relative to pelvis (-2.24°; -3.97 to -0.52). There were however, no significant between-group differences for; global angles of lateral trunk flexion at front foot contact (FFC) (1.2°; -2.5 to

4.8), global angles of lateral trunk flexion ball release (BR) (-0.5°; -3.0 to 2.0), pelvis rotation FFC (0.9°; -4.0 to 2.2), pelvis rotation BR (-1.1°; -5.7 to 3.6), front hip angle FFC (1.6°; -3.6 to 6.7), front hip angle BR (-1.6°; -5.0 to 1.9), front knee angle FFC (-1.1°; -4.5 to 2.3), front knee angle BR (1.7°; -5.6 to 9.1), or ball velocity (1.1 km/h; -7.5 to 9.7).

This thesis demonstrates that the TRIPP framework can used to successfully guide the process of injury prevention in community-level adolescent pace bowlers. The IPP in this thesis was also able to modify several neuromuscular and biomechanical risk factors, however a number of measures were not altered. Future research is needed to refine the current IPP and investigate if it can reduce injury risk in a real-world setting.

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I would like to start by thanking my primary supervisor, Alasdair Dempsey. I'm very thankful for all the advice and expertise you have provided me throughout my PhD. I would also like to extend my thanks to my co-supervisors Brendan Scott, and Jeffrey Hebert. The help and guidance you have given me over the past few years has been greatly appreciated.

My thanks must also go to my fellow postgraduate students who were always there to provide advice, assistance and support throughout my PhD. I also value the time we were able to spend together outside of university. I would also like to acknowledge all the practicum students who assisted during data collection. Without your help my research would not have been possible. Likewise, I would like to thank all the cricket clubs/schools, coaches and participants who took part in my research.

Finally, to my friends, family and partner Jasmine. Thank you so much for always being there throughout my PhD. You have all helped in your own unique ways and I'm very thankful to have such a wonderful support network around me.

List of Abbreviations

IPP	Injury prevention program
TRIPP	Translating Research into Injury Prevention Practice
RPE	Rate of perceived exertion
QL	Quadratus lumborum
PROSPERO	International Prospective Register of Systematic Reviews
PRISMA	Preferred Reporting Items for Systematic Review and Meta-Analysis
RR	Risk ratio
GRADE	Grading of Recommendation, Assessment, Development and Evaluation
MRI	Magnetic resonance imaging
FFC	Front foot contact
BR	Ball release
BFC	Back foot contact
LBP	Low back pain
OR	Odds ratio
SEBT	Star Excursion Balance Test
FIFA	Fédération Internationale de Football Association
ACWR	Acute chronic workload ratio
N.m	Newton meters
%LL	Percent of leg length
CONSORT	Consolidated Standards of Reporting Trials
ICC	Intraclass correlation coefficient
QTM	Qualisys Motion Capture
ANOVA	Analysis of variance

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Peer reviewed manuscripts

Forrest MRL, Scott BR, Hebert JJ, Dempsey AR. Injury Prevention Strategies for Adolescent Cricket Pace Bowlers. *Sports Med*. 2018;48(11):2449-61.

Forrest MRL, Hebert JJ, Scott BR, Brini S, Dempsey AR. Risk Factors for Non-Contact Injury in Adolescent Cricket Pace Bowlers: A Systematic Review. *Sports Med*. 2017;47(12):2603-19.

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Forrest MRL, Scott BR, Hebert JJ, Dempsey AR. Exercise-based Injury Prevention for Adolescent Pace Bowlers. Sports Medicine Australia Conference, Perth, AUS. 2018.

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CHAPTER 1

GENERAL INTRODUCTION

1.1 Introduction

Sport participation provides an important opportunity for adolescents to increase physical activity, which can reduce their risk of type II diabetes, cardiovascular disease and various forms of cancer [1]. Increased physical activity can also promote bone health and improve mental health [2, 3]. However, sport is also the number one cause of injury in adolescent individuals [4]. Sports injuries can increase the risk of future injury, lead to physical inactivity, and cause drop out [5-7]. The prevention of injury through the adolescent years is therefore vital for maintaining the various benefits associated with sport.

Sporting injuries also place a substantial economic burden on the community. In a study from the Flemish Region, the direct medical cost of sporting injury in one year was an estimated €15 million (AU$26 million) [8]. In another study from the Australian state of Victoria, the direct cost of hospital-treated sports injuries in individuals >15 years of age was an estimated AU$265 million over a seven-year period [9]. Alarmingly, research has also revealed a 24% increase in hospital-treated sports injuries and 26% increase in lower-limb sport injuries over the past seven years in individuals >15 years of age [9]. The development and wide-scale implementation of injury prevention strategies for community-level athletes is therefore an important research focus at the current time [9].

Cricket, which is a popular youth sport in many countries and associated with a moderate risk of injury, presents as an appropriate target for injury prevention [10]. Seasonal incidence rates in youth cricket are between 114-242 injuries/1000 participants and these are comparable to those seen in youth soccer (107 injuries/1000 participants) [11, 12]. When examining injury rates relative to hours of exposure, junior and community-level cricketers sustain 130 injuries (per 10,000 hours of play), tennis players 40 injuries, soccer players 35 injuries, and basketballers 33 injuries [10].

Most injuries in youth cricket are attributed to bowling (33-51% of all injuries), whereas batting injuries and those related to fielding account for 11-34% and 23-37% of all injuries, respectively [12-14]. When looking further into bowling-related injuries, we see most of these occurring in the pace bowlers [13-16]. A pace bowler is a player who bowls at such a speed that the wicketkeeper is required to stand back from the stumps in order to field the ball [17]. In a study by Kumar et al [16], 50% of pace bowlers and 23% of spin bowlers sustained an injury over a season. Milsom et al [13] also observed a similar trend, with approximately three times as many injuries occurring in pace bowlers than spin bowlers. When examining injury rates relative to the number of balls delivered, pace bowlers also sustain more injuries than spin bowlers (16.5 injuries/100,000 balls compared to 6.6 injuries/100,000 balls, respectively) [15].

Despite the injury patterns in community-level youth pace bowlers, there is a lack of intervention research aimed at reducing their injury rates. In other sports exercise-based injury prevention programs (IPPs), which increase muscle strength, muscle endurance, and balance/control, have reduced injury risk by approximately 32-45% [18-20]. Evidence also shows that IPPs such as the FIFA (Fédération Internationale de Football Association) 11+ and the FootyFirst program can be successfully delivered at the community-level [21, 22]. Exercise-based IPPs could therefore present as a viable option for reducing injury risk in community-level adolescent pace bowlers. The overarching aim of this thesis was to therefore develop and test the efficacy of a specific IPP for community-level youth pace bowlers.

Before developing an IPP for community-level adolescent pace bowlers, it is important to consider the Translating Research into Injury Prevention Practice (TRIPP) framework [23]. In Stage 1, the framework highlights the need to survey injury rates to identify common/severe injuries. In Stage 2, the framework outlines the importance of uncovering risk factors for these injuries. Following this, preventive programs are developed (Stage 3) and then tested in 'ideal'

settings (Stage 4). In Stage 5 the various barriers/facilitators to program implementation are considered and in Stage 6, program effectiveness is assessed in real-world contexts.

If we consider the TRIPP framework in the context of youth pace bowlers, there is a considerable amount of research detailing injury patterns (Stage 1). Broad injury locations have been well documented in bowlers, with approximately 11-12% of all injuries occurring in the upper-limb, 26-30% in the lower-limb and 53-56% in the back/trunk [13, 24]. When looking further into the upper-limb, the shoulder is the most common injury area accounting for 9-16% of all injuries in adolescent pace bowlers. [25, 26]. In the lower-limb, knee and ankle/heel injuries are common. Knee injuries account for 34-41% of all injuries and are typically attributed to patellofemoral pain and Osgood-Schlatter disease [25, 27]. It is important to note, however, that some investigations involving adolescent pace bowlers report no knee injuries [26, 28, 29]. As for injuries in the ankle/heel, these account for approximately 8-19% of all injuries in youth pace bowlers and most present as ligament sprains [27] or calcaneal apophysis (Sever's disease) [26]. The majority of back/trunk injuries are to the low back which account for 37-64% of all reported injuries in adolescent pace bowlers [26, 28, 29]. The majority of these injuries affect the lumbar soft tissues (such as the muscle, tendons, ligaments and intervertebral discs) or the lumbar vertebrae [26, 30, 31]. Lumbar vertebrae injuries typically include, stress reactions, spondylolysis, and spondylolisthesis [26, 30, 31].

The one-year incidence of symptomatic lumbar vertebral injury in adolescent pace bowlers is 11-12% [26, 30, 31] and four-year incidence is 24% [32]. These injuries are almost exclusively associated with bowling and occur with a gradual on-set [32]. Bowlers who are diagnosed with a lumbar vertebral injury are generally required to stop bowling for 8-12 weeks and it is typically 6-12 months before bowlers can return to full competitive match-play [32].

Again, when applying the TRIPP framework to community-level adolescent pace bowlers, a large quantity of research has uncovered risk factors for injury (Stage 2). Broadly,

these risk factors include; poor bowling biomechanics, inappropriate bowling load, and neuromuscular deficiencies [26, 28, 31, 33]. While these individual studies provide us with vital information, a systematic review of this literature has not been conducted. The quality of this research and the relative importance of each risk factors is therefore unclear.

While the injury patterns and risk factors for injury are well documented in community-level adolescent pace bowlers, there is a lack of research situated in Stages 3 and 4 of the TRIPP framework. Evidence from other sports indicates that exercise-based IPPs can reduce injury risk, but a specific program for community-level adolescent pace bowlers has not been developed. Furthermore, the efficacy of exercise-based IPPs to modify risk factors for injury in adolescent pace bowlers has not been investigated. The primary aim of this thesis was to develop a specific IPP and test if this program can modify risk factors for injury in community-level adolescent pace bowlers.

1.2 Statement of the Problem

Sporting injuries are on the rise and wide-scale injury prevention strategies are needed in community sport. Injury patterns and injury risk factors in adolescent pace bowlers are well established (in line with Stages 1 and 2 of the TRIPP framework), but this risk factor literature has not been systematically reviewed. This makes it difficult to design appropriate IPPs for community-level pace bowlers (Stage 3 of the TRIPP framework), and as such, there are currently no specific exercise-based recommendations available for this group. Furthermore, in line with Stage 4 of the TRIPP framework, we do not know if IPPs can modify risk factors for injury in community-level adolescent pace bowlers. Table 1.1 provides an overview of the thesis' contributions in the context of the TRIPP framework.

Table 1.1 Thesis contribution and the TRIPP framework.

	TRIPP Stage [a]	Current research [b]	Thesis contribution
1	Injury surveillance	Well documented	
2	Establish aetiology and mechanism of injury	Well documented (no systematic review)	Study 1
3	Develop preventitive measures	Research needed	Study 2
4	Scientific evaluation in ideal conditions	Research needed	Study 3 Study 4
5	Describe intervention context to inform implementation strategies	Research needed	
6	Evaluate effectiveness of preventitive measeures in implementation context	Research needed	

[a] Adapted from Finch [23], [b] in the context of community-level adolescent pace bowlers.

1.3 Purpose and Aims of the thesis

The aim of this thesis was to systematically review risk factors for injury in adolescent pace bowlers (Study 1, Chapter 2) and then develop a specific IPP for community-level adolescent pace bowlers (Study 2, Chapter 3). The thesis also aimed to test the efficacy of this newly-developed IPP to modify neuromuscular risk factors for injury (Study 3, Chapter 4) and alter bowling kinematics linked to low back injury (Study 4, Chapter 5). The title and primary aim of each study is presented below.

Study 1 (Chapter 2)

Risk factors for non-contact injury in adolescent cricket pace bowlers: a systematic review

    a) Identify the risk factors for non-contact injury in adolescent cricket pace bowlers.

Study 2 (Chapter 3)

Injury prevention strategies for adolescent cricket pace bowlers

    a) Provide rationale and present an IPP specific to community-level adolescent pace bowlers.

Study 3 (Chapter 4)

Exercise-based injury prevention for community-level adolescent cricket pace bowlers: a cluster-randomised controlled trial

    a) Investigate changes in muscle strength, dynamic neuromuscular control, and trunk extensor endurance following an eight-week exercise program.

Study 4 (Chapter 5)

Modifying bowling kinematics in cricket pace bowlers with exercise-based injury prevention: a cluster-randomised controlled trial

    a) Investigate changes in bowling kinematics following an eight-week exercise program.

1.4 Significance of the research

The research comprising this thesis is situated in Stages 2, 3 and 4 of the TRIPP framework. The thesis is the first to systematically review risk factors for injury in adolescent pace bowlers. It also presents a newly-developed exercise program and investigates if this can modify neuromuscular deficiencies and alter kinematics of the bowling action. Policy makers who wish to promote the uptake of exercise-based injury prevention within their respective playing cohorts could use the findings in this thesis to inform their approach. Community-level cricket coaches with limited experience in exercise prescription could also implement the exercise program presented in this thesis to modify risk factors in their playing group. While future research is still needed, this thesis ultimately lays the foundation for future advancements in the area of injury prevention for community-level adolescent pace bowlers.

1.5 Limitations and assumptions

A number of limitations exist within this thesis. In Chapters 4 and 5 the outcome assessor was not blind to group allocation at follow-up. Some of the outcome scores may therefore be prone to bias. Nevertheless, most outcomes in Chapters 4 and 5 were assessed objectively, and these measures are typically less susceptible to bias. The kinematical bowling data in Chapter 5 may also lack ecological validity as they were collected in a controlled laboratory environment. Measurement error due to skin movement while bowling could have also affected the validity of the kinematic data. While there are limitations associated with 3D motion capture, it is important to note that this method is the currently the gold-standard in biomechanical data collection.

Due to financial and practical constraints, wearable technologies were not used to quantify bowling load. Instead, players recorded their bowling load in a logbook. Although this method may be prone to recall bias, the primary researcher met with each player on a weekly

basis to ensure their logbooks were up to date. It was also difficult to collect comprehensive training load data in Chapters 4 and 5. While rating of perceived exertion (RPE) data were collected during the training sessions associated with this study, if a player trained with an additional cricket organisation, their RPE data was not collected.

1.6 Delimitations

Overall generalisability of the findings in this thesis may be limited. For example, the majority of studies identified in the systematic review (Chapter 2) and the studies presented in Chapters 4 and 5, involved male, adolescent pace bowlers playing cricket in Australia. The participants partaking in Chapters 4 and 5 also had limited resistance training experience. The findings in this thesis may therefore lack generalisability to players outside this cohort.

The exercise program utilised in this thesis was also delivered by the primary researcher not the team coach. While this allowed program-efficacy to be tested under 'ideal conditions', it limited the external validity of the findings. In a real-world setting, where the coach would typically deliver the program, adherence and compliance rates may differ to those seen in the current thesis. Furthermore, the exercise program was only implemented over an eight-week period, which may not reflect the context of implementation where programs are typically delivered over the entire season. It is also important to note that the effect of the IPP to reduce injury risk was not directly targeted in this thesis, owing to time and monetary limitations

CHAPTER 2

RISK FACTORS FOR NON-CONTACT INJURY IN ADOLESCENT CRICKET PACE BOWLERS: A SYSTEMATIC REVIEW

Based on the following paper published in *Sports Medicine*

Forrest MRL, Hebert JJ, Scott BR, Brini S, Dempsey AR. Risk factors for noncontact injury in adolescent cricket pace bowlers: a systematic review. Sports Med. 2017;47(12):2603–19.

2.1 Abstract

Background: Adolescent cricket pace bowlers are prone to injury. Recognising the risk factors for non-contact injury in this population will aid future injury prevention strategies. *Objective*: To identify the risk factors for non-contact injury in adolescent cricket pace bowlers. *Methods:* PubMed, Cochrane Library, PEDro, SPORTDiscus, Embase, and the South African Journal of Sports Medicine were systematically searched to identify all experimental and observational studies reporting risk factors for non-contact injuries in pace bowlers (aged 12-19 years). The search syntax included terms relevant to cricket bowling, injury, and known risk factors for injury. The Newcastle-Ottawa Quality Assessment Scale and a modified Newcastle-Ottawa Quality Assessment Scale were used to assess the risk of bias in the cohort and cross-sectional studies, respectively. *Results*: Sixteen studies (5 cross-sectional studies, 11 cohort studies), comprising 687 participants (96% male, 75% playing cricket in Australia) met the selection criteria and were included for qualitative synthesis. Three cross-sectional studies were rated as high risk of bias and two as very high risk of bias. For the cohort studies, three were rated as low risk of bias, and eight as high risk of bias. Injury was associated with bowling biomechanics (excessive lateral trunk flexion and pelvis/hip kinematics), reduced trunk endurance, poor lumbo-pelvic-hip movement control, and early signs of lumbar bone stress. Conflicting results were found by studies examining the mixed technique, bowling workload, and quadratus lumborum (QL) asymmetry. *Conclusions:* The current systematic review identified a number of bowling biomechanics and various neuromuscular deficiencies as risk factors for non-contact injury in adolescent pace bowlers. These factors may provide a useful target for future interventional research aiming to prevent injury in this population. Future studies should utilise prospective cohort designs; and ensure that participants are injury free at baseline, confounding factors are well controlled, and attrition rates are reported.

2.2 Introduction

Injury prevalence rates are high in cricket pace bowlers and similar to those seen in individuals playing contact sports such as rugby union and Australian Football [34-36]. The majority of pace bowling injuries are attributed to the bowling action, where ground reaction forces approximate 4-6 times body weight, and lumbar shear forces are 40-50 times greater than those experienced during running [37-39]. Pace bowlers are most commonly injured in the lower back and lower-limb regions, with lumbar stress fractures considered the most debilitating injury, typically resulting in 6-12 months of missed playing time [32, 40].

A recent systematic review of studies investigating injury risk factors among adult pace bowlers reported bowling biomechanics, bowling workload, neuromuscular factors, and previous injury as risk factors for non-contact injury [41]. Similarly, an earlier systematic review by Morton et al. [42] identified bowling biomechanics, neuromuscular factors, and previous injury as risk factors specific for low back injury. No prior systematic review however, has comprehensively reported on risk factors for all non-contact injuries among adolescent pace bowlers. This represents an important gap in knowledge as adolescent cricketers are more prone than adult cricketers to back/trunk injuries, overuse injuries, [14] and growth-related conditions common to the lower extremities (e.g., Osgood-Schlatter disease and Sever's disease) [43]. The knowledge surrounding risk factors for injury in adolescent pace bowlers will help guide future injury prevention research. Therefore, the aim of this systematic review is to identify the intrinsic and extrinsic risk factors for non-contact injury in adolescent pace bowlers.

2.3 Methods

2.3.1 Protocol and registration

This systematic review was registered a priori with the International Prospective Register of Systematic Reviews ((PROSPERO), CRD42016043956) and reported in accordance with

Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA guidelines) [44].

2.3.2 Eligibility criteria

Full-text, peer-reviewed studies that investigated risk factors for non-contact injury in pace bowlers aged 12-19 years were included. Eligible study designs included randomised controlled trials; as well as prospective and retrospective cohort, cross-sectional, and case-control studies. Unpublished studies, case reports, editorials, books, letters, and conference proceedings were excluded. There were no restrictions on language; or the country of origin, sex of participants, or playing level of participants.

Injuries were defined in accordance with the international consensus statement on injury surveillance in cricket and therefore included match time-loss injuries, general time-loss injuries, medical attention injuries, player-reported injuries, and imaging-abnormality injuries [45]. Non-contact injuries were defined as those which occurred without a collision mechanism (colliding with another player or being hit by the bat/ball) and therefore included both sudden and gradual-onset non-contact injuries [45]. If injury mode (contact or non-contact) was ambiguous, the site of injury was considered in the determination of injury mechanism. This is consistent with previous approaches of classifying bowling injuries to the shoulder, low back, and lower-limb as non-contact injuries [41].

2.3.3 Information sources

A comprehensive search strategy was developed in consultation with a reference librarian and implemented in the following databases from inception to 2 May 2016: PubMed, Cochrane Library, PEDro, SPORTDiscus, and Embase. The South African Journal of Sports Medicine was also searched, as relevant articles were identified in this journal during the preliminary search process. The articles contained within this journal however, were not indexed in the aforementioned databases. The search syntax was initially developed for PubMed (Systematic

Review Syntax) utilising Medical Subject Headings (MeSH) and index terms, and then adapted for use in the other databases and the South African Journal of Sports Medicine. The search syntax included terms relevant to cricket bowling, injury, and known risk factors for injury. The reference lists of all included articles were manually searched to identify any remaining studies.

2.3.4 Study selection

Using Covidence software [46], two review authors (MF and AD) independently screened the titles and abstracts of all identified articles to determine their eligibility. The full-text of eligible studies was then evaluated independently by the two review authors. Disagreements regarding article inclusion at each stage were resolved through discussion with a third review author (JH).

2.3.5 Data collection process

Two review authors (MF and SB) used a customised data extraction form to collect the following information from each study: design, participant information (number of participants, definition of playing position, sex of participants, age of participants, playing level of participants and country in which the study took place), exposure definition (risk factor/s identified), outcome definition (type of injury examined, mechanism of injury and anatomical position of injury), and study results (mean, standard deviation, risk ratios (RR) and statistical significance). If data were unobtainable, the corresponding author was contacted for additional information. Disagreements between the two review authors (MF and SB) regarding study design, participant information, exposure/outcome definition and study results were resolved through discussion with a third review author (JH).

2.3.6 Risk of bias assessment

A modified Newcastle-Ottawa Scale for cross-sectional studies (Appendix B) [47] and the Newcastle-Ottawa Scale for cohort studies (Appendix C) [48] were applied independently by two review authors (MF and SB) to assess the risk of bias of included studies (at the study level).

Two sections on the Newcastle-Ottawa Scale for cross-sectional studies [47] were modified to realign this scale with the rating system from the Newcastle-Ottawa Scale for cohort studies [48]. This was achieved by substituting the "ascertainment of exposure" and "assessment of outcome" sections from the Newcastle-Ottawa Scale for cohort studies into the Newcastle-Ottawa Scale for cross-sectional studies. A maximum of nine stars were available for the cohort studies and eight stars available for the cross-sectional studies. Disagreements between the two review authors (MF and SB) on risk of bias ratings were resolved through discussion with a third review author (JH). Studies awarded ≥ 7 stars were deemed to be at low risk of bias, 4-6 stars at high risk of bias and ≤ 3 stars at very high risk of bias [49].

2.3.7 Data synthesis

A random-effects meta-analysis was planned and the Grading of Recommendation, Assessment, Development and Evaluation (GRADE) [50] considered if studies were found to be clinically and statistically homogeneous. The planned meta-analysis was not performed, and the GRADE summaries of evidence quality were not applied [50], owing to clinical heterogeneity between studies. Consequently, a qualitative synthesis of the included studies was performed.

2.4 Results

2.4.1 Study selection

A flow diagram outlining the study selection procedure is presented in Figure 2.1. The search strategy yielded 1889 articles. After removing duplicates, 1265 articles were included in the title/abstract screening, and 126 articles were retained for full-text review. Articles were removed following full-text screening due to incorrect publication type ($n = 25$), non-cricket population ($n = 11$), adult population ($n = 52$), no injury outcome ($n = 8$), and no risk factor investigated ($n = 14$). Following this screening process, sixteen articles were included [25-28, 30, 31, 33, 51-59].

2.4.2 Study characteristics

The sixteen eligible studies in this systematic review included five cross-sectional and 11 cohort studies, comprising a total of 687 participants. Mean/median age of the included participants ranged from 13.2-19.0 years [52, 59]. Age range was not reported in four studies [33, 51-53] and five studies reported an age range which included participants who were <12 or >19 years (the mean age in all of these studies fell between 12-19 years) [25, 27, 28, 30, 59]. One study included both male and female participants [57] while the remaining studies included only male participants.

The majority of studies (75%) were conducted in Australia [26, 28, 30, 31, 33, 51-54, 56-58], with two studies (12.5%) taking place South Africa [25, 55] and two (12.5%) in England/Wales [27, 59]. Three studies (18.7%) included club/district/school level pace bowlers [26, 30, 33] and two studies (12.5%) included pace bowlers from a range of skill levels (district to state level [31] and club to national level [54]). Playing level was not reported in one investigation [58], with the remaining 10 studies (62.5%) comprising elite level cricket players (state/provincial/county/national) [25, 27, 28, 51-53, 55-57, 59].

Bowling speed was reported in four investigations [31, 51-53] and five studies included fast bowlers who were identified by their coaches as such, or who delivered the ball at a speed that required the wicketkeeper to stand back from the stumps to field the ball [26-28, 30, 59]. One study included cricketers from a mix of playing positions but identified risk factors for injury in players who had suffered a low back injury due to bowling or a comparable action (e.g., an injury attributed to rotating, extending or laterally flexing the trunk during a task other than bowling) [57]. The remaining six studies did not explicitly define their bowlers but did report their participants as being fast bowlers in either the title or text [25, 33, 54-56, 58].
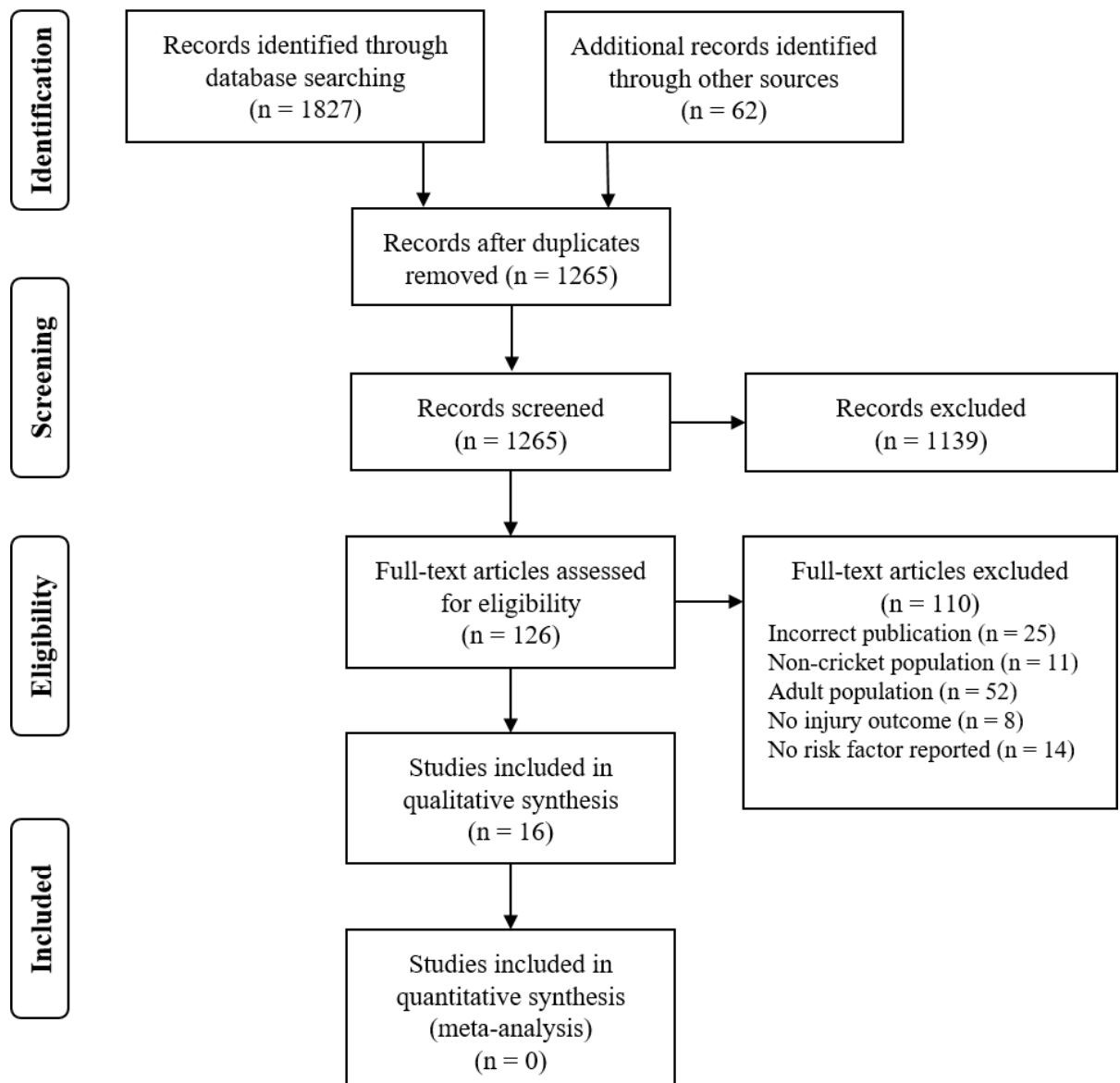
Figure 2.1 Flow diagram of studies through the systematic review.

2.4.3 Risk of bias within studies

Risk of bias was assessed within five cross-sectional studies; three of these were rated as high risk of bias and two as very high risk of bias [51, 53, 55-57] (Table 2.1). Three major sources of bias were found within the cross-sectional studies which typically failed to justify sample size [51, 53, 55-57], report the number of non-respondents [51, 53, 55, 56], or control for confounding factors [53, 55-57]. Of the 11 cohort studies, three were rated as low risk of bias and eight as high risk of bias [25-28, 30, 31, 33, 52, 54, 58, 59] (Table 2.2). Three major sources

of bias also existed in the cohort studies which typically failed to report if participants were injured at baseline [26, 28, 30, 53-55, 58], control for confounding factors [26, 27, 30, 33, 52, 54, 58, 59], or report the number of participants lost to follow-up [25, 26, 28, 30].

Table 2.1 Newcastle-Ottawa Quality Assessment Scale for cross-sectional studies.

Study	Selection				Comparability		Outcome		Total [a]
	1	2	3	4	1a	1b	1	2	
Elliott et al. [51]	*	-	-	*	-	*	*	-	4
Elliott et al. [53]	*	-	-	*	-	-	*	*	4
Gray et al. [55]	*	-	-	*	-	-	-	*	3
Hardcastle et al. [56]	*	-	-	*	-	-	*	-	3
Hecimovich et al. [57]	*	-	*	*	-	-	-	*	4

[a] Total is out of 8 stars.

Table 2.2 Newcastle-Ottawa Quality Assessment Scale for cohort studies.

Study	Selection				Comparability		Outcome			Total [a]
	1	2	3	4	1a	1b	1	2	3	
Bayne et al. [31]	*	*	*	*	*	*	*	*	*	9
Burnett et al. [33]	*	*	*	*	-	-	*	*	*	7
Davies et al. [25]	*	*	*	*	*	*	-	*	-	7
Dennis et al. [28]	*	*	*	-	-	*	*	*	-	6
Dennis et al. [26]	*	*	-	-	-	-	*	*	-	4
Elliott et al. [52]	*	*	*	-	-	-	*	*	*	6
Engstrom et al. [54]	*	*	*	-	-	-	*	*	*	6
Foster et al. [30]	*	*	*	-	-	-	*	*	-	5
Gregory et al. [27]	*	*	-	-	-	-	-	*	*	4
Kountouris et al. [58]	*	*	*	-	-	-	*	*	*	6
Ranson et al. [59]	*	*	*	*	-	-	*	*	*	7

[a] Total is out of 9 stars.

2.4.4 Study Exposures

Eight studies investigated bowling biomechanics such as trunk/pelvis/lower-limb kinematics, lumbar kinetics, and ground reaction forces [28, 30, 31, 33, 51-53, 56]. Bowling workload factors such as bowling quantity and frequency were investigated in six studies [25-28, 30, 31].

A number of neuro-musculo-skeletal factors were also investigated and these included anthropometry/posture [28, 30, 31, 51, 53, 57, 58], QL morphology [54, 58], abdominal muscle morphology [55], bone stress on magnetic resonance imaging (MRI) [59], flexibility [25, 28, 30, 31, 53], muscular strength [28, 30, 51], muscular endurance [28, 30, 31, 51, 53], and lumbo-pelvic-hip movement control [31]. Aerobic capacity was also investigated in two studies [28, 30].

2.4.5 Study Outcomes

Ten studies examined intervertebral disc and vertebral imaging-abnormality injuries [30, 31, 33, 51-54, 56, 58, 59]. Seven of these examined abnormalities in the lumbar spine [31, 52-54, 56, 58, 59], two in the lumbo-sacral region [30, 51], and one in the thoraco-lumbar region [33]. Intervertebral disc abnormalities were defined as disc degeneration, disc bulging, disc herniation, or reduced disc height [33, 51-53, 56], with bony vertebral abnormalities including pedicle sclerosis, pars interarticularis sclerosis, stress reaction of the posterior element of a vertebra, spondylolysis, or spondylolisthesis [30, 31, 53, 54, 56, 58, 59]. Four studies investigated symptomatic abnormalities [30, 54, 58, 59], with another four investigating both symptomatic and asymptomatic abnormalities [31, 33, 53, 56]. In two studies, it was unclear whether the abnormalities were associated with pain [51, 52].

Nine studies defined injury as match time-loss [26, 28, 30, 31], match/training time-loss [25, 55, 57], or a painful/disabling condition [27, 58]. Of these nine studies, six examined injuries to certain anatomical locations; lower back [31, 55, 57, 58], back [30], and back/trunk/lower-limb [28]. The remaining three studies did not restrict injury to an anatomical location and generally recorded injuries to the shoulder, low back and lower-limb (groin, knee, ankle and foot) [25, 27, 28]. Two of the nine studies only examined injuries with a gradual onset [26, 28].

2.4.6 Results of individual studies

The injury risk factors identified in this systematic review included; bowling biomechanics (lateral trunk flexion, technique factors, pelvis/lower-limb kinematics, and ball release height), bowling workload (bowling frequency and bowling quantity), and neuro-musculo-skeletal factors (anthropometry, lumbar posture, longitudinal foot arch, QL morphology, abdominal muscle morphology, bone stress reaction, flexibility, muscular strength, muscular endurance, and lumbo-pelvic-hip movement control) (Table 2.3 and Table 2.4).

2.4.6.1 Lateral trunk flexion

Lateral trunk flexion contralateral to the bowling arm was greater in injured bowlers than non-injured bowlers [31]. This was evident at both front foot contact (FFC) (mean difference 4.9°, $p = 0.039$) and ball release (BR) (mean difference 9.6°, $p = 0.002$). However, there were no differences in lumbo-pelvic lateral flexion range (between FFC and BR) in injured and non-injured bowlers [31].

2.4.6.2 Technique factors

The use of the mixed technique (i.e., bowling with a rotated trunk at back foot contact (BFC) or rotating the shoulders excessively between BFC and FFC) was associated with imaging-abnormality injury in two cohort studies [33, 52]. In the study by Burnett et al. [33], 80% of bowlers (n = 8/10) who utilised the mixed technique at baseline and follow-up showed signs of progressive thoracolumbar disc degeneration whereas, of the bowlers who utilised the mixed technique at one session only (either at baseline or follow-up), only 14% (n = 1/7) showed signs of progressive thoracolumbar disc degeneration ($p = 0.015$).

Shoulder counter-rotation (i.e., excessive shoulder rotation between BFC and FFC) was significantly greater amongst injured bowlers in two cross-sectional studies [53] albeit at an alpha level of 0.1 in one investigation [51]. Elliott et al. [53], reported significantly greater shoulder counter-rotation among bowlers who displayed signs of bony lumbar abnormalities

(median 12°) and intervertebral disc abnormalities (median 25°) compared those who were injury free (median 0°). Conflicting results linking shoulder counter-rotation to injury were reported by three cohort studies [28, 30, 31]. Foster et al. [30] reported relatively low levels of shoulder counter-rotation in uninjured bowlers (16°), whereas, of the bowlers who counter-rotated >40°, 35% sustained a stress fracture and 41% sustained a soft tissue injury to the back. In contrast, Bayne et al. [31] observed no differences in the amount of shoulder counter-rotation utilised by bowlers who sustained a lumbar injury and those who did not (p >0.05). In one cross-sectional study, two other shoulder kinematics were associated with injury; shoulder alignment at BFC, and minimum shoulder alignment [53]. However, other investigations including one cross-sectional study [51] and two cohort studies [28, 30] found no associations between these kinematics and injury.

2.4.6.3 Pelvis and lower-limb kinematics

In one cohort study, pelvic rotation at BR was significantly greater in bowlers who developed a low back injury compared to those who did not (mean difference 10.7°, $p = 0.024$) [31], while no difference (p >0.05) was observed at FFC. In the same study, injured bowlers delivered the ball with a relatively straighter front hip at FFC compared to the non-injured bowlers (mean difference 4.6°, $p = 0.049$) [31]. This was also a characteristic observed by Foster et al. [30], where those who developed stress fractures bowled with a more extended front hip and knee at FFC. A link between an extended front knee at FFC and injury, however, was not reported in other studies [28, 31, 51].

Table 2.3 Cross-sectional study characteristics and results.

Study	Participants	Exposure	Outcome	Results
Elliott et al. [51]	N = 24, mean = 13.7 y, school and club, Australia, male	Bowling kinematics (shoulder rotation)	Lumbar intervertebral disc abnormalities	Bowlers with disc degeneration or disc bulging had greater shoulder counter-rotation ($30.0\pm10.5°$) compared to those who did not ($18.9\pm9.3°$) $p = 0.088$. (alpha level = 0.1 in this study). No significant differences between the groups for a range of bowling kinematics, ground reaction forces, age, muscular endurance, and anthropometry
Elliott et al. [53]	N = 20, mean = 17.9 y, all male, state, Australia	Bowling kinematics (shoulder rotation and ball release height), hamstring/ low back flexibility	Lumbar intervertebral disk degeneration (group 2) and bony vertebral abnormalities (group 3)	Alignment of shoulder at BFC: group 1 (injury free) median 179.0°, group 2 median 206.0°*, group 3 median 197.0°*. Release height/height: group 1 median 110%, group 2 median 113%, group 3, median 114%*. Shoulder alignment at minimum: group 1 median 179°, group 2 median 181°, group 3 median 193°*. Minimum - BFC (shoulder counter-rotation): group 1 median 0°, group 2 median -25°*, group 3 median -12°*. Age: group 1 (16.4 y), group 2 (17.4 y), group 3 (18.4y)*. Sit and reach: group 1 (8.0cm), group 2 (4.5cm)*, group 3 (10.5cm). No differences between the groups for a range of bowling kinematics, ground reaction forces, posture, muscular strength, muscular endurance, and anthropometry
Gray et al. [55]	N = 25, mean(range) 17 and 16 (14-18) y, all male, provincial, South Africa	Abdominal muscle morphology	Current LBP which had existed for at least six weeks. The pain originated from fast bowling and caused at least one missed game or training session	LBP group had larger abdominal muscle CSA on the non-dominant side ($p = 0.01$). Non-LBP group had no differences in the CSA of the dominant and non-dominant sides ($p = 1.0$). LBP group had reduced abdominal muscle CSA on the non-dominant side 2.4 ± 0.4cm, compared to the non-LBP group 3.0 ± 0.4cm, $p = 0.03$. No difference in CSA on the dominant side (LBP group 2.5 ± 0.4cm, non-LBP group 2.5 ± 0.4cm, $p = 1.0$). LBP group had reduced internal oblique CSA compared to the non-LBP group ($p = 0.02$). No difference between the groups when examining the external oblique and transversus abdominis muscle CSA. The CSA of the muscles on the non-dominant side of the non-LBP bowlers was always larger ($p <0.001$). In the LBP group, the CSA of the individual muscles was symmetrical ($p = 0.01$)

Study	Participants	Exposure	Outcome	Results
Hardcastle et al. [56]	N = 24, mean(range) = 17.9 (16-18) y, all male, state, Australia	Bowling kinematics (mixed action)	Lumbar pars interarticularis defects, intervertebral disc degeneration and LBP	Of the bowlers with a mixed technique who rotated <10°, 83% (n = 5/6) displayed signs of both lumbar abnormality and LBP. Of the bowlers with a mixed technique who rotated >10°, 100% (n = 10/10) displayed signs of lumbar abnormality and 80% (n = 8/10) of these had LBP
Hecimovich and Stomski [57]	N = 59, mean(range) = 14.3 (13-17) y, male/female, state, Australia	Lumbar lordosis	Match/training time-loss injury to the lower back associated with bowling/similar action	Lumbar lordosis was significantly greater in bowlers with a history of low back injury (42.53±9.10°) compared to those with no history of low back injury (30.33±8.36°) (p <0.01)

*Values are mean±SD unless otherwise indicated. List abbreviations; y (years), LBP (low back pain), CSA (cross-sectional area), * (significant difference compared to injury free group (p <0.05))*

Table 2.4 Cohort study characteristics and results.

Study	Participants	Exposure	Outcome	Results
Bayne et al. [31]	N = 25, mean(range) =15.8 (14-19) y, all male, district/state, Australia	Bowling kinematics (trunk, pelvis and lower-limb), lumbar bowling kinetics, trunk endurance, and reduced movement control	Match time-loss injury to the low back, and asymptomatic signs of lumbar bone stress	Compared to non-injured bowlers, injured bowlers had lower front hip angle at FFC ($46.1\pm5.6°$; $50.7\pm5.5°$, p = 0.049), greater thorax lateral flexion at FFC ($19.9\pm6.0°$; $15.0\pm5.1°$, p = 0.039), increased pelvis rotation at BR ($287.3\pm10.8°$; $276.6\pm11.4°$, p = 0.024), increased thorax lateral flexion at BR ($49.8\pm5.9°$; $40.2\pm7.8°$, p = 0.002), higher peak lumbar flexion/extension moment (10.5 ± 4.9 Nm.kg–1.m–1; 6.9 ± 2.5 Nm.kg–1.m–1, p = 0.036), higher peak lumbar lateral flexion moment (12.5 ± 2.6 Nm.kg–1.m–1; 10.6 ± 1.9 Nm.kg–1.m–1, p = 0.049), higher peak lumbar lateral flexion power (25.8 ± 16.2 W.kg–1.m–1; 14.4 ± 7.7 W.kg–1.m–1, p = 0.043), reduced Biering-Sorensen test hold time (103 ± 33s; 132 ± 33s, p = 0.037) and increased knee valgus angle during single leg decline squat on dominant ($9\pm3°$; $5\pm4°$, p = 0.031) and non-dominant sides ($9\pm4°$; $6\pm3°$, p = 0.027). No significant between group differences in lumbar kinetics, ground reaction forces, shoulder counter-rotation, lumbo-pelvic ROM while bowling, joint ROM (ankle dorsiflexion and internal/external hip rotation), muscular endurance, lumbo-pelvic stability, foot arch height, a range of bowling kinematics and bowling workload
Burnett et al. [33]	N = 19, mean = 13.6 y, all male, school/club, Australia	Bowling kinematics (mixed action)	Progressive degeneration of the thoracolumbar intervertebral discs	Eighty percent of the bowlers with a mixed technique at both baseline and follow-up showed signs of progressive thoracolumbar disc degeneration whereas only 14% of the bowlers utilising a mixed technique at one session (baseline or follow-up) showed signs of progressive thoracolumbar disc degeneration (p = 0.015). More bowlers showed signs of thoracolumbar disc degeneration at 16.3 y of age (58%) compared with those who were 13.6 y of age (21%) (p = 0.008). No significant relationships between thoracolumbar disc degeneration and bowling with a mixed technique at session 1 only or bowling with a mixed technique at session 2 only

Study	Participants	Exposure	Outcome	Results
Davies et al. [25]	N = 46, mean(range) = 14.6 (11-18) y, all male, national, South Africa	Bowling workload and, hamstring flexibility	A condition which prevents normal cricketing activity	Hamstring flexibility was reduced in players who missed playing time due to injury compared to those who did not: Pre-season (mean difference 8.6°, $p = 0.003$), mid-season (mean difference 7.4°, $p = 0.015$), average for the season (mean difference 6.7°, p = 0.006). No difference in post season hamstring flexibility (mean difference 2.3°, p = 0.542). Bowling workload was significantly related to weeks injured (Pearson's correlation (r) = 0.62, p <0.0005). Recurrent injuries accounted for 43% of injuries
Dennis et al. [28]	N = 91, median(range) =17.8 (12.3-33.1) y, all male, state, Australia	Hip internal rotation ROM and ankle dorsiflexion ROM	Insidious condition to the back, trunk or lower-limb associated with bowling. Affected match selection/ performance or resulted in surgery	Reduced internal hip rotation ROM on the leg ipsilateral to the bowling arm was associated with a reduced injury risk (≤30° vs >40°, OR = 0.20, 95 % CI 0.06-0.73). Conflicting results between reduced ankle dorsiflexion lunge on the leg contralateral to the bowling arm and injury risk (12.1–14.0 cm vs >14 cm, OR = 4.03, 95 % CI 1.07-15.21 and ≤12 cm vs >14 cm, OR = 1.38, 95 % CL 0.04-4.48). No significant relationship between injury and shoulder counter-rotation, a range of bowling kinematics, joint ROM (knee extension, hip extension/abduction/external rotation), muscular strength, muscular endurance, aerobic capacity and anthropometry
Dennis et al. [26]	N = 44, mean(range) = 14.7 (12-17) y, all male, club/district, Australia	Bowling workload	Insidious condition affecting match selection/ performance or requiring surgery	Fewer days rest between bowling sessions increased injury risk (<3.5 days compared to ≥ 3.5 days, RR = 3.1, 95 % CI 1.1-8.9). Injured bowlers had significantly fewer days between bowling sessions compared to the non-injured bowlers (median 3.2, median 3.9, p = 0.038). No significant increase in injury risk when bowling ≥ 2.5 days per week (RR = 2.5, 95 % CI 0.9-7.4), bowling ≥ 50 deliveries per day (RR = 2.0, 95 % CI 0.7-5.4) and bowling ≥ 100 deliveries per week (RR = 1.2, 95 % CI 0.4-3.4)
Elliott et al. [52]	N = 41, mean = 13.2 and 13.4 y, all male, state, Australia	Bowling kinematics (mixed action)	Lumbar intervertebral disk abnormalities	Bowlers who utilised the mixed technique had significantly increased levels of lumbar disk degeneration when compared to bowlers utilising the front-on or side-on action ($p = 0.002$)

Study	Participants	Exposure	Outcome	Results
Engstrom et al. [54]	N = 51, mean =13-17 y, all male club to national, Australia	QL muscle morphology	Symptomatic lumbar pars lesions	Increasing risk of a symptomatic L4 pars lesions with increasing asymmetry, 105% QL asymmetry = 4%, 95 % CI 0.01%-17% risk of a symptomatic L4 pars lesions, 125% QL asymmetry = 58%, 95 % CI 32%-80% risk of a symptomatic L4 pars lesions and, 130% QL asymmetry = 78%, 95 % CI 45%-93% risk of a symptomatic L4 pars lesions. No significant associations between the combined CSA of the erector spinae/multifidus and injury
Foster et al. [30]	N = 82, mean(range) = 16.8 (15-22) y, all male, club/school, Australia.	Longitudinal foot arch, quadriceps torque, shoulder strength, bowling kinematics (shoulder counter-rotation and ball release height), and bowling workload	Match time-loss injury to the vertebra or soft tissue of the back	Compared to the non-injured bowlers, those who developed a stress fracture had lower longitudinal foot arch height, greater non-dominant quadriceps strength, greater amounts of shoulder counter-rotation and released the ball from a higher point (p <0.05). Compared to the non-injured bowlers, those who developed a back injury had greater shoulder depression strength and shoulder horizontal flexion strength on the bowling arm side (p <0.05). They also displayed a more front-on shoulder alignment at BFC. Fifty nine percent of participants who bowled in >17 matches sustained a stress fracture or back injury (total injury incidence rate of 38%). Bowling >10 overs in a day resulted in a relatively high number of players (66%) reporting back pain the next day. No significant differences between the groups when examining ground reaction forces, a range of bowling kinematics, anthropometry, muscular strength, muscular endurance, joint ROM, aerobic capacity, and posture
Gregory et al. [27]	N = 70, mean(range) = 15.3 (9-21) y, all male, county, England	Bowling workload	A condition associated with bowling that reduced bowling performance or prevented bowling	No significant link between injury incidence (injuries per 1000 balls bowled) and the quantity of balls bowled over a six-month period (0-1000 balls bowled = 0.258 injuries/1000 balls, 1000-2000 = 0.236, 2000-3000 = 0.147, and >3000 = 0.067 (p = 0.180). No significant difference between the injury rates of the bowlers delivering <1000 balls (20 injuries/100 bowlers) and those delivering >1000 balls (36.4 injuries/100 bowlers (p = 0.232). No significant difference in the percentage of injured bowlers in the group who bowled >3000 balls and the group who bowled 1000–3000 balls (mean difference 3.7%, 95 % CI –30%-29%)

Study	Participants	Exposure	Outcome	Results
Kountouris et al. [58]	N = 38, mean(range) = 14.9 (12-17) y, all male, Australia	QL muscle morphology	Lumbar bone stress or lumbar soft tissue injuries	The quantity of individuals with QL asymmetry (<10%, 10-20% and, >20%) was not significantly different between groups (lumbar bone stress injury, lumbar soft tissue injury and no injury $p = .180$). No differences in average asymmetry between those with lumbar soft tissue injuries (12.5% asymmetry), lumbar bone stress injuries (15.7%) and non-injured (12.4%) ($p = .537$). Average asymmetry did not differ significantly between the bowlers with lumbar bone stress injuries (15.7%) and those without (12.4%) ($p = 0.267$). Four bowlers who had asymptomatic signs of lumbar bone stress at pre-season went on to develop a symptomatic stress fracture during the cricket season. Lumbar stress fracture group had significantly greater body mass index (22.6±1.73) compared to non-lumbar stress fracture group (20.7±1.72) (p <0.05). No significant differences between the groups when examining age, height, and weight

Values are mean±SD unless otherwise indicated. List abbreviations; y (years), CSA (cross-sectional area), ROM (range of motion), QL (quadratus lumborum), 95 % CI (confidence interval), RR (risk ratio), OR (odds ratio).

2.4.6.4 Ball release height

Ball release height was associated with injury in one cross-sectional [53] and one cohort study [30]. Foster et al. [30], however, did not present the ball release height values, so the magnitude of association cannot be judged. In the cross-sectional study by Elliott et al. [53], the bony abnormality group released the ball from a greater height (114% of their standing height) compared to bowlers in the non-injured group (110% of their standing height) ($p \leq 0.05$). In a number of other studies, no significant associations were found between injury and ball release height, both when examining release height as an absolute value [53] or as a value relative to standing height [28, 51].

2.4.6.5 Lumbar kinetics

Lumbar moments and lumbar power between FFC and BR were significantly greater in bowlers who developed a low back injury compared to those who did not [31]. This included greater peak lumbar flexion/extension moments (mean difference 3.6 Nm.kg^{-1}.m^{-1}, $p = 0.036$), greater peak lumbar lateral flexion moments (mean difference 1.9 Nm.kg^{-1}.m^{-1}, $p = 0.049$), and higher peak lumbar lateral flexion power (mean difference 11.4 W.kg^{-1}.m^{-1}, $p = 0.043$). No significant difference existed between the injured and non-injured bowlers when examining peak lumbar force (anterior/posterior, vertical, and medio/lateral), peak lumbar rotation moment, and peak lumbar power (flexion/extension and rotation) [31].

2.4.6.6 Other biomechanical factors

A number of notable bowling biomechanics were not associated with injury and these included approach velocity [30, 31, 51, 53], ball speed [28, 51, 53], angle of back foot at BFC [30, 51, 53], stride length between BFC and FFC [28, 51, 53], lumbo-pelvic range of motion (flexion/extension, and rotation) [31], and ground reaction forces at BFC and FFC (both vertical/compressive and breaking/horizontal forces) [30, 31, 51, 53].

2.4.6.7 Bowling frequency

Injured bowlers had significantly fewer days' rest between bowling sessions compared to non-injured bowlers (median difference 0.7 days, $p = 0.038$). A significant increase in injury risk was also observed in bowlers who had <3.5 days' rest between bowling session compared to those with ≥ 3.5 days' rest (RR = 3.1, 95 % confidence interval (CI) 1.1-8.9) [26]. In the same investigation, no significant increase in injury risk was observed when bowling ≥ 2.5 days per week (RR = 2.5, 95 % CI 0.9-7.4) [26].

2.4.6.8 Bowling quantity

Conflicting results were found linking bowling quantity to injury in five cohort studies [25-27, 30, 31]. Davies et al. [25], for example, found a significant relationship between mean balls delivered per week and playing time lost to injury over the course of a season (Pearson's $r = 0.62$, $p <0.0005$). However, in another investigation, no significant increase in injury risk was found when bowling ≥ 50 deliveries per day (RR = 2.0, 95 % CI 0.7-5.4) and when bowling ≥ 100 deliveries per week (RR = 1.2, 95 % CI 0.4-3.4) [26]. Likewise, Gregory et al. [27] found no significant link between the quantity of balls bowled over a six-month period and injury incidence ($p = 0.180$) and Bayne et al. [31] reported no significant differences in a variety of bowling workload factors (average number of overs per week and per session, average sessions per week and maximum number of overs in one session, one week, two weeks and four weeks) between bowlers who did and did not develop a low back injury over the course of a season ($p >0.05$).

2.4.6.9 Anthropometry

In one cohort study, body mass index was significantly greater in bowlers who sustained a stress fracture compared to those who did not (mean difference 1.9, $p <0.05$) [58]. In other investigations,

no significant associations were found between injury and body fat percentage [28, 30, 51, 53], height [28, 51, 53], or body weight [28, 30, 51, 53].

2.4.6.10 Lumbar posture and longitudinal foot arch

In a cross-sectional investigation, lumbar lordosis was significantly greater (mean difference 12.2°, $p <0.01$) in bowlers with a history of low back injury compared to those with no history of low back injury [57]. In one cross-sectional study [53] and another cohort study [30], however, no association was found between lumbar lordosis and lumbar imaging-abnormality injuries and low back injuries, respectively. A low longitudinal foot arch was a characteristic of bowlers who sustained a lumbar stress fracture in one cohort study ($p <0.05$) [30]. In other investigations, including one cross-sectional study [18] and one cohort study [31], no associations were found between longitudinal foot arch height and injury.

2.4.6.11 QL morphology

Conflicting results linking QL asymmetry to injury were found within two cohort studies [54, 58]. In the investigation by Engstrom et al. [54], for example, increased QL asymmetry (greater cross section area on the side ipsilateral to the bowling arm) was significantly linked with sustaining a stress fracture. This was particularly evident in bowlers with >130% QL asymmetry who had a 78% (95 % CI 45-93%) chance and bowlers with 125% QL asymmetry who had a 58% (95 % CI 32-80%) chance of sustaining a lumbar stress fracture. Conversely, bowlers with lower QL asymmetry (105%) only had a 4% (95 % CI 0.01-17%) chance of sustaining a lumbar stress fracture [54]. In the investigation by Kountouris et al. [36], no significant differences in QL muscle asymmetry existed between non-injured bowlers and those who sustained a lumbar soft tissue injury or a lumbar bone stress injury over the course of the season ($p = 0.537$).

2.4.6.12 Abdominal muscle morphology

In bowlers with low back pain (LBP), the combined cross-sectional area of the abdominal muscles (external oblique, internal oblique, and transverse abdominis) was not significantly different between the dominant and non-dominant sides ($p = 1.0$), yet in bowlers with no LBP, it was significantly greater on the non-dominant side ($p = 0.01$) [55]. There were no differences in abdominal muscle cross-sectional area (dominant side) between the LBP and non-LBP groups; however, the non-LBP group had larger cross sectional area on the non-dominant side (mean difference 0.6 cm, p = 0.03) [55]. Combined thickness of the internal oblique (dominant side + non-dominant side) was reduced in the LBP group compared to the non-LBP group ($p = 0.02$). There was no difference between groups when examining combined thickness of the external oblique ($p = 1.0$) or the transverse abdominis ($p = 1.0$) [55].

2.4.6.13 Bone stress reaction

In the cohort study by Ranson et al. [59], early bone stress reaction, as identified with MRI, was associated with future lumbar stress fracture ($p <0.001$). Eleven of 15 bowlers in this study with signs of bone stress at baseline went on to develop a stress fracture approximately 10 weeks later. Similarly, in the investigation by Kountouris et al. [58], all four bowlers with asymptomatic lumbar stress reactions at baseline developed a symptomatic bone stress injury later in the season.

2.4.6.14 Flexibility

In the cohort study by Dennis et al. [28], conflicting results were found when linking ankle dorsiflexion range (ankle dorsiflexion lunge test) to injury. For example, bowlers with 12.1-14 cm of range were at an increased risk of injury (12.1–14.0 cm vs >14 cm, odds ratio (OR = 4.03, 95 % CI 1.07-15.21), whereas bowlers with ≤ 12 cm of range were not (12 cm vs >14 cm, OR = 1.38,

95 % CL 0.04-4.48). In the cohort study by Bayne et al. [31], no link was found between ankle dorsiflexion range of motion and low back injury.

Hamstring flexibility (straight-leg raise test) was significantly reduced in players who missed playing time due to injury over the course of a season compared to those who did not [25]. This was evident at pre-season (mean difference 8.6°, $p = 0.003$) mid-season (mean difference 7.4°, $p = 0.015$), and when averaged across the season (mean difference 6.7°, $p = 0.006$) [25]. A significant difference was not observed when examining post season hamstring flexibility (mean difference 2.3°, $p = 0.542$) [25]. Likewise, in two other cohort studies, no link was found between reduced hamstring flexibility and the development of lumbar stress fractures [30] or back/trunk/lower-limb injuries [28].

Conflicting results were found in two cohort studies examining hip rotation range of motion [28, 31]. Reduced hip internal rotation range on the leg ipsilateral to the bowling arm, for example, was significantly associated with a reduced risk of injury in one study (OR = 0.20, 95 % CI 0.06-0.73) [28]. In the same investigation, however, neither contralateral hip internal rotation range nor external hip rotation range were linked to injury [28]. Bayne et al. [31] also reported no significant differences in internal or external hip rotation range between bowlers who did and did not sustain a low back injury over the course of a season.

2.4.6.15 Muscular strength

In the cohort study by Foster et al. [30], greater isokinetic quadriceps torque (60°/s) in the leg contralateral to the bowling arm was significantly associated with stress fractures, and increased shoulder strength in the bowling arm (depression strength and horizontal flexion strength) was linked with back injuries (p <0.05). In the same investigation, isokinetic hamstring strength (60°/s), trunk flexion strength and trunk extension strength were not significantly different between injured

and non-injured bowlers [30]. Likewise, in the cross-sectional study by Elliott et al. [53], trunk flexion strength, trunk extension strength, and trunk flexion/extension strength ratio were not significantly different between injured and non-injured bowlers.

2.4.6.16 Muscular endurance

In one cohort study, reduced hold time on the Biering-Sorensen test, an assessment of trunk extensor muscle endurance, was a characteristic of bowlers who sustained a low back injury (mean difference 29 s, $p = 0.037$) [31]. No significant associations between injury and the following assessments of muscular endurance were found in several studies; calf endurance test [28, 31], sit-up endurance test [30, 51, 53], prone plank hold [28, 31], single leg bridge hold [28, 31], and side plank hold [31].

2.4.6.17 Movement control

Bowlers who sustained a low back injury had significantly greater medial knee movement during a single leg decline squat [31]. This was evident in both the dominant limb (mean difference 4°, $p = 0.031$) and non-dominant limb (mean difference 3°, $p = 0.027$). In the same investigation, a score of "0" on a lumbo–pelvic stability test was not significantly associated with an increased risk of injury (RR = 1.7, 95 % CI 0.78-4.10) [31].

2.5 Discussion

The current systematic review identified risk factors for non-contact injury in adolescent pace bowlers aged 12-19 years. Bowling biomechanics, bowling workload, and neuro-musculo-skeletal factors were commonly investigated, with potentially modifiable risk factors including lateral trunk flexion, pelvis/hip kinematics, reduced trunk endurance, and poor lumbo-pelvic-hip movement control [25-28, 30, 31, 33, 51-59]. Conflicting results were found amongst the studies investigating

the mixed technique [28, 30, 31, 33, 51-53], bowling workload [25-27, 31], and QL asymmetry [54, 58].

2.5.1 Risk of bias within studies

The cross-sectional studies did not report sample size calculations and were potentially underpowered and prone to type II error. Many cross-sectional and cohort studies also failed to control for potential confounding factors, which may limit the internal validity of these results. The majority of cohort studies did not report whether the study outcome (i.e., injury) was present at baseline and, therefore, may have included injured participants at baseline. Dropout rates were not well reported in a number of cohort studies, making it difficult to assess for attrition bias and external validity at follow-up.

2.5.2 Risk factors

Excessive lateral trunk flexion contralateral to the bowling arm at both FFC and BR was associated with low back injury in one cohort study with low risk of bias [31], and these findings accord with studies of adult fast bowlers [60]. Contralateral lateral trunk flexion occurs at a time when compressive and shear forces acting on the body are high [37, 38] and towards the side where the majority of lumbar stress fractures occur in pace bowlers [56, 61]. Continued research is needed to confirm excessive lateral flexion as a risk factor for injury; however it may prove a good target for modification.

The mixed action was linked with thoracolumbar disc degeneration in two cohort studies at low [33] and high [52] risk of bias respectively. When examining shoulder counter-rotation (a component used to classify the mixed action) the cohort studies at lower risk of bias found no significant association between this factor and injury [28, 30, 31], whereas cross-sectional studies with a higher risk of bias did [51, 53, 56]. Furthermore, in two cohort studies examining the

kinematics used to classify the mixed action at BFC (angle of back foot and shoulder alignment), no link was found between these factors and injury [28, 30]. The influence of the mixed action on injury therefore remains unclear and further research is needed to determine whether this factor influences injury.

Conflicting results were found in both the cross-sectional [51, 53] and cohort studies [25, 30] examining the relationship between ball release height and injury. In a low risk of bias cohort study, bowling with a more extended hip at FFC was associated with low back injury [31]. This is similar to findings reported in adult pace bowlers, where bowling with an extended knee at FFC was linked with trunk injury [62]. Bowling with a straighter lower-limb may reduce the capacity to attenuate forces while bowling and increase the shear forces affecting the lumbo-pelvic region [38, 62]. Bowling with an extended lower-limb, however, is an important aspect for producing faster ball speeds [38, 62]. While modification of lower-limb kinematics may have implications for reducing injury risk [38, 62], recent work has found that faster bowlers can have straighter front legs while also having lower vertical ground reaction forces [63].

There were contrasting results within cohort studies examining bowling workload in both the studies at low [25, 31] and high risk of bias [26, 27]. Workload was self-reported in all studies and potentially prone to recall bias. In another study, the bowling workload data were incomplete and excluded from analysis [28]. It is unclear if the other studies examining workload also had difficulties with incomplete data [25-27, 31]. The contrasting findings could also be explained by the method in which the workload data was analysed. In adult pace bowlers for example, spikes in acute workload (one week) relative to chronic workload (one month) have been shown to increase the risk of injury [64]. There is also evidence to support a potential U-shaped distribution in the relationship between workload and injury, with moderate workloads protecting against injury and

low/high workloads increasing the risk of injury [41]. Future research examining bowling workload as an injury risk factor should ensure that the association between acute/chronic workloads and the potential U-shaped relationship between workload and injury are considered.

The role of QL asymmetry is unclear with two high risk of bias cohort studies reporting conflicting results [54, 58]. Neither study excluded individuals with asymptomatic bone stress at baseline, the methods used to measure QL cross-sectional area differed between studies, and one study investigated L4 stress fractures [54], while the other examined a combination of L4 and L5 stress fractures [58]. Biomechanical investigations suggest a potential link between certain bowling biomechanics (lumbo-pelvic lateral flexion measurements) and QL asymmetry [38]. Neither Engstrom et al. [54] nor Kountouris et al. [58], however, controlled for bowling biomechanics and this could have potentially confounded the results. Finite element modelling studies question the role of QL asymmetry in the development of injury [65]. While QL asymmetry may be associated with injury, the causal nature of this association remains unclear. Future research aiming to establish the role of QL asymmetry in bowling-related injuries should ensure that participants are injury-free at baseline and bowling biomechanics are controlled for.

Neuromuscular dysfunction may lead to injurious movements while bowling and potentially exposes bowlers to injurious loads [31, 66]. In one low risk of bias cohort study, reduced trunk extensor endurance and poor lumbo-pelvic-hip movement control were associated with injury [31]. These factors are also associated with injury in other populations and their potential for modification makes them a good target for intervention [67-69].

2.5.3 Limitations

Clinical heterogeneity prevented the quantitative synthesis of study results and limited the application of GRADE summaries of evidence quality [50]. Study heterogeneity also limited my

ability to assess publication bias. It is therefore unclear if publication bias influenced the findings in this review. A comprehensive search strategy developed in consultation with a reference librarian was implemented in several major databases; however, it is possible that relevant articles were not identified during the search process.

No consistent definition was used to define a fast bowler and only four studies reported bowling speed [31, 51-53]. It was therefore difficult to compare cohorts across studies. A number of investigations also failed to explicitly state whether they examined contact or non-contact injuries and the studies investigating workload were potentially limited by recall-bias. Most included studies were conducted on elite, male pace bowlers playing cricket in Australia and the results of this review may not generalise to individuals outside this cohort. Furthermore, there was a lack of evidence regarding risk factors for non-low back injuries, with only four studies examining injuries outside this location.

2.5.4 Future research

Future studies investigating risk factors for injury in adolescent pace bowlers should ensure that participants are injury free at baseline, confounding factors are controlled, and attrition rates reported. Weight-normalised bowling speeds should also be reported in future investigations to allow comparisons to be made between cohorts. Injury type and mode (contact or non-contact) should be reported in accordance with the international consensus statement on injury surveillance in cricket [45], to allow for easier comparisons between studies and sporting codes. There is also a need to more accurately measure bowling workload, as self-reported methods can be problematic in adolescent individuals [28]. Recent developments using microsensor technology may serve as a useful tool, although these methods require further validation in adolescent pace bowlers [70]. Female pace bowlers and pace bowlers playing cricket outside of Australia were not well

represented in the current review and further research is needed to identify risk factors for injury in these populations. Injury records from epidemiology studies also highlight the need to identify risk factors for injuries occurring outside the low back, such as those to the shoulder, groin, knee, ankle and foot [14, 40].

Several potentially modifiable risk factors were identified in this review and these could be the target of future interventional studies. Exercise-based interventions should be considered in adolescent pace bowlers as these programs are effective in modifying neuromuscular risk factors and reducing injuries in adolescent athletes [20]. It would also be beneficial to investigate whether certain biomechanical features are modifiable, such as excessive lateral trunk flexion during the bowling action. Care must be taken when modifying any factor to ensure performance is not compromised and that additional risk factors are not introduced. When implementing injury prevention strategies, it is also important to consider the ecological validity of these methods [71]. Interventions which are costly, time consuming, and reliant on expert knowledge may have limited practical application.

2.6 Conclusion

A number of potentially modifiable risk factors are associated with non-contact injury in adolescent cricket pace bowlers and these include excessive lateral trunk flexion while bowling, pelvis and hip bowling kinematics, reduced trunk extensor endurance, and poor lumbo-pelvic-hip movement control. MRI may be helpful to identify individuals who are prone to developing future lumbar stress fractures. There were conflicting findings regarding the mixed technique, bowling workload, and QL asymmetry. Further research is needed to understand the influence of these factors on injury. Future investigations examining injury risk factors in adolescent pace bowlers should utilise prospective cohort study designs and ensure the major sources of within-study bias identified in

this review are minimised where possible. It would also be beneficial to assess if exercise-based IPPs are effective for modifying neuromuscular factors and coaching interventions are useful for bowling technique modification.

CHAPTER 3

INJURY PREVENTION STRATEGIES FOR ADOLESCENT CRICKET PACE BOWLERS

Based on the following paper published in *Sports Medicine*

3.1 Abstract

Adolescent cricket pace bowlers are prone to non-contact shoulder, low back and lower-limb injuries. Exercise-based IPPs are effective for reducing non-contact injuries in athletes; however, a specific program for adolescent pace bowlers has not been published. This paper therefore seeks to provide a rationale for the development of an exercise-based IPP specific for adolescent pace bowlers. It also outlines design principles and provides an example exercise program that can be implemented at the community-level. In addition, the paper addresses other injury prevention techniques concerned with the prescription of appropriate bowling loads and the modification of poor bowling biomechanics. Performing an exercise-based IPP before cricket training could reduce injury rates in adolescent pace bowlers. Eccentric strengthening exercises can be employed to target injuries to the posterior shoulder muscles, hip adductors and hamstring muscles. The risk of low back, knee and ankle injury could also be reduced with the inclusion of dynamic neuromuscular control exercises and trunk extensor endurance exercises. Other prevention strategies that need to be considered include the modification of poor bowling biomechanics, such as shoulder counter-rotation and lateral trunk flexion. Coaches and players should also aim to quantify bowling load accurately and coaches should use this information to prescribe appropriate individualised bowling loads. Specifically, players would benefit from avoiding both long periods of low load and acute periods when load is excessively high. Future evidence is needed to determine the effectiveness of the example program outlined in this paper. It would also be beneficial to investigate whether the modification of bowling biomechanics is achievable at the non-elite level and if bowling load can be accurately measured and manipulated within a community-level population.

3.2 Introduction

Sporting activities are a major cause of injury in adolescent individuals [9]. These injuries are associated with costly medical expenses [9], result in sports dropout [72], decrease sport performance at the team/individual level [73] and increase the risk of developing a future sporting injury [74]. For adolescent athletes aiming to advance to elite senior competition, some injuries can also represent a serious threat to their career. Cricket pace bowlers have similar injury prevalence rates to athletes playing high-contact football codes, prompting research interest in the area of injury prevention for pace bowlers [34, 35, 40]. Within this field, attention has been particularly focused on adolescent pace bowlers, who are susceptible to certain injuries during their developmental years [75, 76]. Adolescent individuals, for example, have partially ossified lumbar vertebrae, elastic intervertebral discs, immature articular cartilage prone to micro-damage and elongated musculotendinous tissues [77-79]. Consequently, non-contact injuries frequently occur in adolescent pace bowlers and typically affect the shoulder, low back (e.g., lumbar stress fractures) and lower-limbs [13, 24, 25, 27, 28].

In Chapter 2, neuromuscular deficiencies, poor bowling biomechanics and bowling load were identified as risk factors for non-contact injury in adolescent pace bowlers [80]. These factors are potentially modifiable, but it can be difficult to change bowling biomechanics without elite coaching staff [81], and at the community-level it is challenging to quantify and then determine appropriate individualised bowling loads [80, 82]. Exercise-based IPPs, however, are effective for modifying neuromuscular risk factors and have been shown to reduce injury risk by 32% in community-level adolescent athletes [20]. Although IPPs also have associated challenges at the community-level, evidence shows that appropriately designed programs can be successful [20]. Nevertheless, no such program has been developed or published specific to adolescent pace

bowlers, despite their considerably high injury prevalence rates and the unique physical demands of the pace bowling action.

Educating community-level cricket coaches about the benefits of IPPs and providing practical education about program delivery would likely increase the chance of implementation and improve player adherence after a program was implemented [21, 83, 84]. Therefore, the primary aim of this paper is to provide coaches with exercise-based recommendations to reduce injury risk in community-level adolescent pace bowlers. A secondary aim is to highlight additional injury prevention strategies which could be considered by community-level cricket coaches, such as the manipulation of bowling biomechanics and the moderation of bowling loads.

3.3 Exercise Program Design Principles

When developing an IPP for adolescent pace bowlers, it is important to consider the unique demands of the bowling action and understand the principles outlined in the TRIPP framework [23]. The TRIPP framework highlights the importance of identifying common/debilitating injuries, uncovering injury mechanisms and risk factors, considering the context of program implementation and developing effective preventive programs [23]. Sections 3.3.1–3.3.4 highlight important considerations regarding these factors and provides coaches with an understanding of the underlying rationale and challenges associated with implementing an IPP specific to adolescent pace bowlers.

3.3.1 Bowling Action

Adolescent pace bowlers deliver approximately 55 balls per match and more than 100 deliveries per week in-season [26]. The bowling action (Figure 3.1) is highly dynamic, combining rapid multi-planar trunk movements with large ground reaction forces. Between FFC and BR, for

example, the spine moves through a combination of extension/ flexion, lateral flexion and rotation [85], while the body experiences ground reaction forces approximately four to six times body weight [37]. The resultant lumbar shear forces during this time reach levels 40–50 times greater than those experienced while running [38]. The repetitive application of these forces to the body is therefore considered an important aetiological factor in the development of non-contact injury in pace bowlers [31, 86].
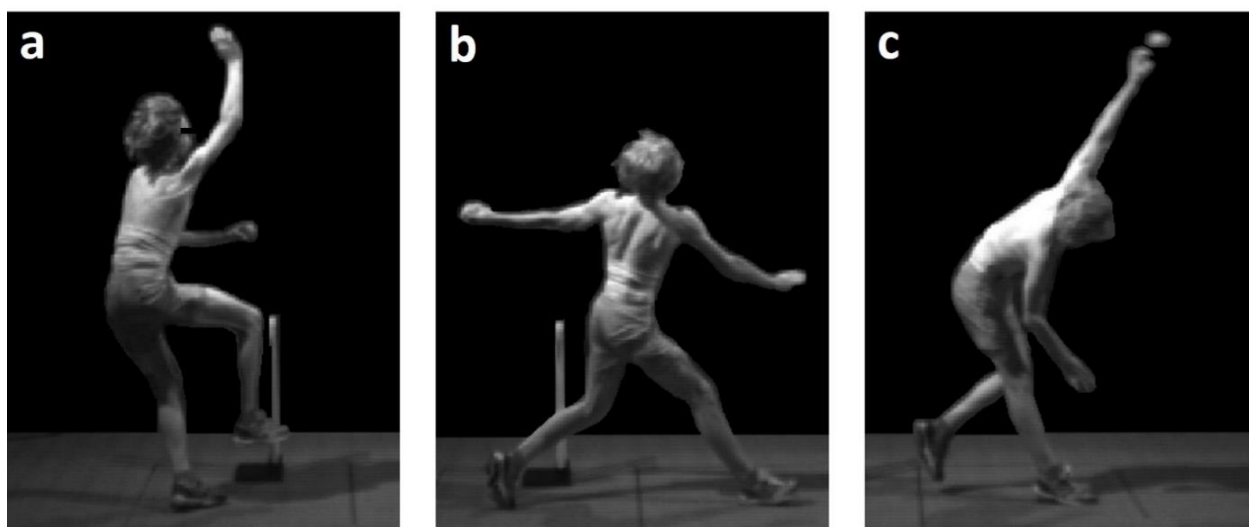

Figure 3.1 The pace bowling action: a BFC; b FFC; and c BR.

3.3.2 Common Injuries

The majority of non-contact injuries in adolescent pace bowlers are to the back/trunk and lower-limbs, with the remainder affecting the upper limbs [13, 24, 25] (Table 3.1). Lumbar spine abnormalities such as spondylolysis and spondylolisthesis have been reported in 11–55% of adolescent pace bowlers [30, 53]. Unilateral lumbar spine abnormalities typically occur on the side opposite the bowling arm at the L4 or L5 spinal level [53, 54] and, when symptomatic, can cause between 6 and 12 months of missed cricket [32]. Thoracolumbar intervertebral disk degeneration has also been reported in 21–65% of adolescent bowlers, although this condition is not always

symptomatic [33, 53]. Pace bowlers may also be susceptible to lumbar muscle strains, which when combined with lumbar stress fractures comprise 47% of all injuries [13].

Common lower-limb injuries include those to the groin, knee and ankle [13, 25, 27, 28]. Groin injuries generally present as muscular strains [13], with those to the knee typically attributed to patellofemoral pain syndrome and Osgood- Schlatter disease [27]. In the ankle, ligament sprains comprise the majority of injuries [13, 27]. Hamstring strains are the most common injury in adult pace bowlers [40] and are more likely to occur in bowlers who have previously sustained a hamstring strain [87]. Prevention of this injury in the adolescent years is therefore important for reducing future injury risk. The shoulder is the most common injury location in the upper limbs [25, 40], with musculotendinous tissues typically affected [13]. Identifying risk factors for injuries affecting the shoulder, low back and lower-limbs (groin, hamstring, knee and ankle) will have the most benefit for adolescent pace bowlers.

Table 3.1 Injury occurrence in adolescent pace bowlers as a percentage of all injuries.

	Stretch [24]	Milsom et al. [13]	Gregory et al. [27]
Upper-limb	11.2	14.8	4.3
Shoulder			4.3
Infraspinatus & deltoid strains		8.8	
Other upper-limb injuries		6.0	
Back & trunk	55.5	53.0	21.7
Low back		47.1	17.4
Other back & trunk injuries		5.9	4.3
Lower-limb	29.5	32.3	73.8
Groin		14.7	4.3
Knee			34.8
Ankle		11.8	26.1
Other lower-limb injuries		5.8	8.6

3.3.3 Neuromuscular Injury Risk Factors

A range of neuromuscular deficiencies exist as risk factors for injury in adolescent pace bowlers (a summary of these factors has been provided in Table 3.2). In the shoulder, eccentric weakness of the external rotators and strength imbalances between internal and external rotators are common risk factors in non-cricket populations [88-90]. Inadequate neuromuscular control (proprioception/movement control) is a risk factor for low back and lower-limb injury in pace bowlers [31, 95, 96], in line with data from other sporting populations [68, 96, 113]. In a study involving adolescent pace bowlers, those who developed a low back injury had reduced neuromuscular control of both dominant and non-dominant lower-limbs during a single-leg decline squat test [31]. Furthermore, reduced reach on the Star Excursion Balance Test (SEBT) has been linked to low back/lower-limb injury in adult pace bowlers [96]. In addition to these proprioception/movement control risk factors, reduced trunk extensor muscle endurance may predispose adolescent pace bowlers to low back injury [31].

Table 3.2 Injury risk factors and exercise-based prevention strategies.

Injury locations	Potential risk factors	Injury prevention strategies
Shoulder	↓ External rotator strength and shoulder strength imbalances [88-90]	Resistance-band strengthening exercises [91-94]
Low back	↓ Dynamic neuromuscular control of the lumbo-pelvic region and lower-limb [31, 95, 96]	Lower-limb strengthening, proprioceptive exercises and plyometric drills [18, 19, 97, 98]
	↓ Trunk extensor endurance [31]	Trunk extensor endurance exercises [99, 100]
Groin	↓ Hip adductor strength and hip strength imbalances [101, 102]	Isometric strengthening and eccentric strengthening exercises [103-105]
Hamstring	↓ Hamstring strength, strength imbalances and ↓ dynamic neuromuscular control of the lower-limb [106-109]	Eccentric strengthening and lower-limb proprioceptive exercises [110-112]
Knee and ankle	↓ Lower-limb proprioception/balance [68, 96, 113]	Lower-limb strengthening, proprioceptive exercises and plyometric drills [18, 19, 97, 98]

↓ *reduced.*

For groin and hamstring injuries, respectively, general weakness of the hip adductor muscles [101, 102] and eccentric weakness of the hamstring muscles [106-108] have been reported as risk factors. It should be noted that these findings come from non-cricket studies and the mechanism of hip adductor and hamstring injury may differ in pace bowlers. Based on the risk factors for shoulder, low back and lower-limb injury, prevention strategies in adolescent pace bowlers should aim to modify muscular strength deficiencies, poor dynamic neuromuscular control and reduced muscular endurance.

3.3.4 Exercise Program Implementation at the Community-Level

Exercise-based programs have been used successfully in a wide variety of sports to modify neuromuscular risk factors and reduce injuries [20]. In baseball pitchers they have been employed to increase posterior shoulder strength [94], in soccer players they have been used to reduce the risk of hamstring and hip adductor injury [105, 111], and in a range of sports these programs have significantly reduced the occurrence of lower-limb injuries [19]. It is evident from these studies that well-designed exercise-based IPPs that take place in relatively controlled environments can be effective for reducing injury risk. However, when designing injury prevention strategies for community-level athletes, it is important to consider the viability of these strategies in a real-world setting [71].

Exercise-based IPPs that fail to consider the context of implementation may have limited uptake, adherence and effectiveness at the community sport level [71]. Identifying which factors facilitate program implementation and considering these factors when designing IPPs may help mitigate these potential issues. The coach, for example, plays a major role in deciding whether an IPP is implemented at the community-level; therefore, designing strategies that accommodate coaches' attitudes and beliefs can be beneficial [84, 114, 115]. Educating players about the benefits

of IPPs and developing fun/enjoyable strategies may also be important for player adherence [84]. The following points should be considered when designing exercise-based IPPs for community-level athletes: (1) incorporate exercises that are simple for the coach and players to learn; (2) use minimal/ inexpensive equipment; (3) include dynamic exercises that act as a warm-up; (4) ensure sessions are time-efficient; and (5) make the sessions fun/enjoyable with the inclusion of partner-assisted exercises and game-/skill-based exercises where possible.

3.4 Evidence−Based Exercise Recommendations

As outlined in section 3.3.4, community-level IPPs need to be effective and simple to implement. With this considered, this section presents a series of exercises that could benefit adolescent pace bowlers competing at the community-level. Strength deficits are commonly related to shoulder injuries in athletes [88-90]. Resistance exercises for the external shoulder rotators are a primary component in the prevention of shoulder injuries in tennis players and baseball pitchers [91-94]. Significant gains in eccentric external rotator shoulder strength have been reported in college tennis players who completed a 5-week shoulder strengthening program incorporating resistance band and dumbbell exercises (78% increase in total work and 30% increase in mean peak force) [92]. Similarly, strength gains of approximately 20% (average force) have been reported in college baseball pitchers who completed a comparable program over a 6-week period [94]. Resistance exercises may therefore be a viable method for correcting strength deficits in pace bowlers at risk of shoulder injury.

As is the case with shoulder injury risk factors, reduced strength is also a risk factor for groin and hamstring injury [102, 106]. The Copenhagen adductor exercise and the Nordic hamstring exercise, respectively, are effective for increasing hip adductor and hamstring strength [103, 105, 112]. In elite soccer players, the introduction of the Copenhagen adductor exercise

significantly increased eccentric hip adductor strength between 9% and 35% [103, 105]. Significant gains in eccentric hamstring strength have been reported amongst elite soccer players who performed the Nordic hamstring exercise over a 10-week period (11% increase in peak torque) [112]. The Nordic hamstring exercise also significantly reduces injury risk among amateur soccer players (OR = 0.28, 95% CI 0.11–0.72) [116]. Not only are the Copenhagen adductor exercise and the Nordic hamstring exercise effective, they are also ideal for amateur athletes. These partner-based exercises can be performed without any additional equipment and are relatively simple to teach and learn.

Strengthening exercises are also vital components in the prevention of low back and lower-limb injuries, especially when combined with balance and plyometric/jumping drills [18, 19, 97, 98]. Squats and lunges are appropriate introductory strengthening exercises and ideal for teaching correct exercise technique to novice athletes. Dynamic single-leg balance exercises are also beneficial in the early stages (i.e., balancing on one leg while catching a ball from a partner) [117-119]. While catching a ball on one leg is not necessarily a cricket-specific movement, it is a dynamic activity with the potential to increase the level of enjoyment. More advanced strengthening exercises (i.e., partner-assisted single-leg squats) and double-leg plyometric/jumping drills are effective exercises in the intermediate stages of a program. These exercises can then become more dynamic with the inclusion of single-leg squats and multidirectional single-leg jumping drills [120, 121]. In a systematic review examining the effect of specific training modalities on injury risk, both strength training (RR = 0.32, 95% CI 0.21–0.48) and proprioceptive programs (RR = 0.55, 95% CI 0.35–0.87) significantly reduced injury risk [18]. Results from another systematic review demonstrate that programs incorporating plyometric/jumping drills are also effective for attenuating injury risk (RR = 0.40, 95% CI 0.35–0.57) [19].

Another element to consider when attempting to reduce low back injury in pace bowlers is trunk extensor endurance. Static hold exercises are effective for targeting improvements in this area and should aim to progress athletes from low-load to high-load positions [122]. The prone hold is an ideal exercise for community-level athletes as it requires no equipment and can easily be progressive with relatively simple adjustments to limb position. In a group of track and field athletes, the prone hold and series of other static hold exercises were included in a program that increased hold time on the Biering-Sorensen trunk endurance test by approximately 20% [100].

3.5 Practical Application of an Exercise‑Based Injury Prevention Program

Five key injury prevention areas for adolescent pace bowlers have been identified: (1) increase eccentric strength of the external shoulder rotators [91]; (2) increase hip adductor strength [102]; (3) increase eccentric hamstring strength [111]; (4) improve dynamic neuromuscular control of the lumbo-pelvic region and lower-limbs [31]; and (5) improve trunk extensor endurance [31]. Practitioners with appropriate qualifications should use the five key prevention areas to guide the design of individualised programs. These individualised programs should consider the needs of the athlete and aim to accommodate individuals returning from injury or those with certain neuromusculoskeletal deficiencies. Coaches also need to consider what exercise equipment they have available and the environment in which the program is being prescribed (e.g., the surface of the training ground or the climatic conditions). Although this individualised context-specific approach to injury prevention is ideal, it is often complex and could act as a major barrier to program implementation at the community-level.

When developing exercise-based IPPs for community-level athletes it is therefore necessary to design generalised programs that accommodate the majority of athletes. The FIFA 11+ and the FootyFirst program are noteworthy examples of IPPs that achieve this [22, 84]. To aid

community-level cricket coaches and others involved with exercise programming in cricket, an example IPP for adolescent pace bowlers was developed (Table 3.3) with an accompanying program manual (Appendix D). As this is just an example program, coaches with appropriate qualifications are encouraged to individualise the exercises for their athletes and tailor the program to suit their environment.

The example program can be performed two times per week (ideally before training) and used in both the preseason and the regular season. The program requires minimal equipment (a cricket bat and ball), includes relatively simple exercises and takes approximately 10–15 min to complete per session. A running warm-up and number of dynamic exercises have also been included in the program, allowing it to be used in place of a usual warm-up. For coaches prescribing this program, it is recommended that they educate players about the potential benefits of participating in IPPs and, where possible, incorporate the exercises into game/skill activities. Coaches are also encouraged to include all players in the example program, not just the pace bowlers in the team.

3.5.1 Exercise Program Progression

Three progressive phases are included in the example program: a basic phase incorporating simple exercises that can be used to teach correct exercise technique (stage 1); an intermediate stage where players continue to build a base of strength, endurance and balance (stage 2); and an advanced phase where the exercises become more sport-specific and dynamic (stage 3). Athletes can begin the program at any stage; however, it is recommended that practitioners screen athletes for neuromuscular deficiencies before deciding which stage is the most appropriate starting point. In the amateur setting where screening athletes may be difficult, it is appropriate to begin all athletes at stage 1.

Table 3.3 Example of an exercised-based IPP for adolescent pace bowlers.

Exercise	Stage	1 - Initial		2 - Intermediate			3 - Advanced		
	Week	1	2	3	4	5	6	7	8
STR	**Posterior shoulder** (resistance-band)	Shoulder abducted 0˚		Shoulder abducted to 45˚			Shoulder abducted to 90˚		
	Volume	2x10		2x10	2x12	2x15	2x10	2x12	2x15
	Posterior shoulder (cricket bat)	Shoulder abducted 0˚		Shoulder abducted to 45˚			Shoulder abducted to 90˚		
	Volume	1x10		1x10	1x12	1x15	1x10	1x12	1x15
	Hip adductor	Side-lying hip adduction		Copenhagen adductor exercise			Copenhagen adductor exercise		
	Volume	1x10		1x4[a]	1x6[a]	1x6[a]	1x8[a]	1x10[a]	1x12[a]
	Hamstring	Nordic hamstring		Nordic hamstring			Nordic hamstring		
	Volume	1x3	1x5	1x6	1x8	1x10	1x12	1x14	1x15
DNC	**Balance**	Single-limb ball throw		Opposite hand to foot			Nil		
	Volume	1x20[a]		1x10[a]	1x12[a]	1x15[a]			
	Lower-limb control	Squats and lunges		Assisted single-leg squat			Single-leg squat		
	Volume	1x10 of each exercise		1x10[a]	1x12[a]	1x15[a]	1x8[a]	1x10[a]	1x12[a]
	Jumping drills	Nil		Double-leg jumps[b]			Single-leg jumps[b]		
	Volume			1x8	1x10	1x12	1x8[a]	1x10[a]	1x12[a]
END	**Trunk extensors**	Prone hold		Prone hold with leg lift			Prone hold with arm + opposite leg lift		
	Volume	20 seconds	30 seconds	1x4[c]	1x6[c]	1x6[c]	1x4[c]	1x6[c]	1x6[c]

List of abbreviations, STR strengthening, DNC dynamic neuromuscular control, END endurance. [a] per leg, [b] jump forwards, to the left and to the right, [c] number of cycles. Volume is expressed as sets x repetitions. Posterior shoulder (cricket bat) exercises should only be performed when resistance-bands are unavailable.

Principles for exercise progression in the example program are in accordance with criteria from other community-level IPPs [84, 119]. Players should therefore progress through the stages on an individual basis when they can complete the prescribed sets and repetitions of an exercise with correct technique (refer to Appendix D for examples of correct exercise technique). It is therefore possible for a player to progress to the next stage for some exercises and remain in their current stage for the others. Before progressing, athletes should also ensure they do not experience excessive delayed-onset muscle soreness. This is particularly important with the eccentric strengthening exercises, where athletes are recommended to wait at least 1–2 weeks before advancing to the next stage [123]. In some contexts, it may be acceptable for coaches to progress all athletes through the phases of the training program at the same time. While this approach may not be optimal for all players, it is more practical for community-level coaches who may have no formal qualifications or experience in exercise coaching.

3.5.2 Performing the Exercise Program

Each exercise session in the example program begins with a dynamic warm-up comprising a range of movements for the upper and lower-limbs (e.g., jogging while swinging the arms in circles, heel flicks, high knees, side steps and shuttle runs). After the dynamic warm-up, players can begin the strengthening exercises, dynamic neuromuscular control drills and muscular endurance exercises. In the initial stage of the program, shoulder external rotator exercises begin with the arm by the side and then progress to positions of 45° shoulder abduction in the intermediate stage and 90° shoulder abduction in the advanced stage. This progression gradually advances the athletes to more unstable shoulder positions and strengthens the shoulder musculature within a sport-specific range of motion. Side-lying hip adductor strengthening exercises are performed in the initial stages to create a base of hip adductor strength before progressing to the more difficult Copenhagen adductor exercise. The Nordic hamstring exercise is prescribed with low repetitions initially and progressed by approximately

1–2 repetitions per week, until 12–15 repetitions can be performed. The low load in the beginning and gradual progression of this exercise minimises the potential effects of delayed-onset muscle soreness. Squats, lunges and a basic single-leg balance exercise are prescribed in the initial stage of the dynamic neuromuscular control component. Partner-assisted single-leg squats, double-leg jumping drills and a more dynamic balance exercise are then incorporated in the intermediate stage. In the advanced stage of the dynamic neuromuscular control component, single-leg squats and single-leg, multidirectional jumping drills are prescribed. As for the static trunk extensor endurance exercises, these are performed with the limbs near the body in the initial stage and then gradually progressed to higher-load positions where the upper and lower-limbs are extended.

All exercise sessions should be supervised by a coach or exercise professional to ensure athlete safety and provide feedback for players who may not have the proprioceptive awareness to determine whether or not they are actually performing an exercise correctly [124]. This is particularly important when performing the dynamic neuromuscular control exercises where inadequate lower-limb control and poor trunk postures can increase the chance of injury [68, 125]. To ensure the athletes receive adequate supervision, coaches should avoid prescribing the program to large groups (i.e., no more than one squad per supervising coach). If a player is having difficulty performing an exercise with correct technique, coaches are encouraged to provide simple analogy-based feedback and focus on modifying one body segment/movement pattern at a time [126, 127]. Tips for providing feedback to bowlers attempting to change movement patterns have been provided in section 3.6.1 and may also assist coaches attempting to teach correct exercise technique.

3.5.3 Additional Benefits of the Exercise Program

Although this program has been designed to reduce the risk of injury in adolescent pace bowlers, it is likely to result in improved bowling performance and benefit other cricketers. Bowlers with

greater strength/power in the lower-limbs and increased lumbo-pelvic control, for example, could potentially bowl faster [128]. This may be achieved through their ability to produce a faster run-up, generate a larger horizontal impulse during the delivery stride and more efficiently mediate ground reaction forces up through the body to the bowling arm [63, 129]. The exercises could also benefit adult bowlers and cricketers in other playing positions. Injuries to the shoulder, low back and lower-limbs (hamstring, groin, knee and ankle), for example, are common in adult bowlers [40]. Batters also sustain the majority of their noncontact injuries to the lower-limbs (hamstring and groin), while non-contact fielding injuries typically affect the shoulder and hamstring [13, 40].

The neuromuscular exercises included in the example program could also have implications for modifying injurious bowling biomechanics in pace bowlers. In other sporting populations neuromuscular training has been used to alter a range of kinematics linked to anterior cruciate ligament injury [121, 130, 131]. In one study, athletes who performed proprioceptive exercises and plyometric drills reduced their knee valgus angle on a single-leg drop task [130]. These results are of interest to adolescent pace bowlers, especially when considering the findings by Bayne et al. [31], where the bowlers who exhibited excessive knee valgus on a single-leg squat test also bowled with increased amounts of lateral trunk flexion range ($r = 0.401$, $p = 0.047$).

3.5.4 Final Considerations for the Exercise Program

Coaches incorporating injury prevention strategies into their cricket program should always consider athlete safety and well-being. Injured athletes or those with a serious health condition should seek medical approval before participating in the example program. In addition, players should not perform an exercise if it causes them pain. If an athlete experiences pain during a stage 2 or stage 3 exercise, it is appropriate to return to the previous stage. Players should be educated about delayed-onset muscle soreness, which may occur after completing certain

exercises. This muscle soreness, however, is a normal part of exercise and usually subsides naturally within a few days [123].

3.6 Other Injury Prevention Strategies

The preventative effect of the example exercise program could be influenced by other factors such as poor bowling biomechanics and bowling load [80]. A comprehensive approach to injury prevention therefore needs to consider modification of these factors. While it may be more difficult for inexperienced community-level cricket coaches to implement strategies to manipulate bowling biomechanics and bowling load, sections 3.6.1 and 3.6.2 will discuss some approaches that could be used to address these factors.

3.6.1 Bowling Biomechanics

Excessive amounts of shoulder counter-rotation, lateral trunk flexion contralateral to the bowling arm (hereafter referred to as lateral trunk flexion) and bowling with an extended lower-limb at FFC/BR can predispose pace bowlers to injury [31, 52, 62]. The extent to which shoulder counter-rotation (rotation of the shoulders between BFC and FFC) influences injury in adolescent pace bowlers is still debated throughout the literature [80]. Despite this, alteration of this factor does not appear to reduce bowling speed or induce other injurious kinematics [81], and modification is therefore still recommended. Excessive lateral trunk flexion is considered to be an important aetiological factor in the development of lumbar injuries and it is also on the side contralateral to the bowling arm where the majority of lumbar stress fractures occur in pace bowlers [31, 54]. Altering the technique of bowlers with excessive amounts of lateral flexion during the delivery stride could therefore protect against low back injury [31]. Bowling with an extended front limb at FFC has been linked to injury [30, 31]; however, it also appears to be an important factor for bowling fast [62]. The potential trade-off between injury risk and

performance should be considered before attempting to modify sagittal plane front-limb kinematics.

Few studies have attempted to modify bowling biomechanics in pace bowlers [52, 81, 132]. One study used a specialised harness to help bowlers align their shoulders and pelvis while bowling [132], and two other studies employed a coaching intervention to modify a range of injurious trunk and lower-limb kinematics [52, 81]. The studies with a coaching intervention reported significant reductions in shoulder counter-rotation, but no study was able to significantly modify lateral trunk flexion or front-limb extension angle [52, 81, 132]. Improving bowling biomechanics is challenging, but the limited research in this area demonstrates that certain kinematics can be modified [52, 81]. The success of these studies, however, is reliant on the expertise of the coaching staff prescribing the intervention [81]. Providing community-level coaches with practical, context-specific techniques to change bowling biomechanics is therefore essential.

Before attempting to modify a bowler's technique, it is important to understand the motor control principles that underpin the process of motor skill acquisition. For example, coaches need to be aware that it is necessary to (1) focus on modifying one body segment/movement pattern at a time; (2) provide visual and verbal feedback (use analogies and do not overload the player with complicated cues); (3) provide prescriptive knowledge of performance (highlight errors and provide tips for correction/demonstrate the desired movement pattern); (4) avoid providing feedback after every bowling delivery and gradually decrease feedback frequency as the bowler adopts the desired movement pattern; (5) remain positive and be aware of potential decrements in performance during the initial stages of technique modification; and (6) ensure bowling speed and accuracy are not compromised [126, 127, 133, 134]. It is also important to note that not all bowlers require alterations to their bowling action, and in some cases, maintenance as opposed to modification is required. Once

these basic motor skill acquisition principles are considered, coaches can begin to assist players who require changes to their bowling action.

Several movement patterns can influence the amount of shoulder counter-rotation or lateral trunk flexion that occurs during a bowler's action. Experienced coaches can identify these 'poor' movement patterns and provide individualised tips for alteration; however, for the less-experienced coach this may be difficult. Coaches are therefore recommended to use analogy-based feedback to teach their bowlers to align the levers of their body towards the target and carry good momentum through the crease towards the batter [135]. To achieve this, the following points may be useful: (1) during the run-up bowlers should lean their torso slightly forward, have a powerful leg drive and move the arms/legs straight through the sagittal plane); (2) during the delivery stride, the non-bowling arm should align towards the target and pull straight down close to the body; (3) the legs/torso/arms should drive towards the target during the delivery stride (i.e., avoid unwanted movements of the arms and legs across the midline/out to the side of the body); and (4) the bowler should follow through towards the target with a strong hip drive on the dominant leg and continue to pull the front arm through close to the body.

At the community-level, video recording bowlers with a smartphone/tablet at training is a viable method for providing visual feedback. Although the bowling action involves dynamic, multi-planar movements, two-dimensional video footage can be used to identify lateral trunk flexion angles and sagittal plane front-limb kinematics [136]. When recording a bowler's lateral trunk flexion at BR, a camera positioned directly behind the bowler is ideal. If attempting to examine lateral trunk flexion at FFC, a camera placed at an angle perpendicular to the bowler's back at FFC is required [136]. For front-limb kinematics and shoulder counter-rotation, respectively, a side-on camera and a camera positioned directly above the bowler during the delivery stride would be required.

Although outside the scope of this section, poor throwing biomechanics are also likely to increase the risk of shoulder injury. There is, however, limited research in this area focused on cricket pace bowlers and, for this reason, it is difficult to make recommendations to coaches regarding throwing technique modification. Experienced coaches may have the ability to recognise and correct poor throwing technique, and these coaches are encouraged to do so. When attempting to modify throwing biomechanics it is still important to consider the motor control principles outlined earlier in this section.

3.6.2 Bowling Load

Various measures of external and internal load have been identified as risk factors for injury in pace bowlers [41, 80]. External load is often simply described as the number of balls bowled or the number of bowling sessions per week [137]. Internal load, on the other hand, refers to a bowler's level of physiological and psychological stress [137]. The most common and practical method to calculate internal load involves multiplying a bowler's sessional RPE for a training session or a match (using a 0–10 category ratio scale) by the duration of that session in minutes [64].

High absolute external loads can increase injury risk in pace bowlers. In one study there were significant differences in the average number of balls bowled between the injured bowlers (235 deliveries per week averaged over the season) and the bowlers who remained injury free (165 deliveries per week) [64]. Furthermore, individuals bowling >203 deliveries per week increased their injury risk by approximately six times compared with those bowling ≤203 deliveries per week [138]. It is hypothesised that the repetitive application of these high loads to the body can cause micro-tissue damage which eventually accumulates to result in injury [139]. While it may appear intuitive that bowlers would benefit from simply reducing external loads throughout a season, this is likely an inadequate approach to moderating load-associated injuries.

To illustrate, Dennis et al. [17] have demonstrated that both low and high absolute external loads can increase injury risk. Bowlers who averaged 123–188 balls per week over the season were at a lower risk of injury than those who delivered <123 balls or >188 balls [17]. Likewise, bowlers with approximately 3–4 days' rest between bowling sessions over the season were significantly less likely to sustain an injury than those with <2 days' or ≥5 days' rest between bowling sessions [17]. Bowlers may therefore benefit from maintaining moderate loads, rather than simply reducing bowling load altogether [17]. Moderate loads may promote positive neuromusculoskeletal adaptations, which could prepare bowlers to more effectively attenuate the large forces experienced while bowling [82]. Low bowling loads, on the other hand, may physically decondition a bowler and ultimately increase their risk of injury [82]. While it is important to consider absolute load over the course of a season, recent research has revealed that spikes in acute load (1 week) relative to chronic load (1 month), termed the acute chronic workload ratio (ACWR), can also influence injury risk [29, 64].

ACWRs can be determined separately for both external and internal load by dividing the average weekly load over the past month by the load in the current week [29, 64]. If determining an ACWR for external load, a bowler who delivered 20 overs in the current week and averaged 10 overs per week in the past month would have an ACWR for external load of 200%. Likewise, if a bowler's internal load was 2000 arbitrary units in the current week and their average weekly internal load over the past month was 1000 arbitrary units, their ACWR for internal load would be 200%. In a study by Warren et al. [29], adolescent pace bowlers with an ACWR for external load of ≥ 142% were 1.6 times more likely to sustain an injury. Likewise, Hulin et al. [64] demonstrated that a high ACWR (200%) for both external and internal load increased injury risk by 3 and 4.5 times, respectively. Load-related injury risk increases when bowlers are exposed to substantially high acute loads. These spikes in load can induce neuromuscular fatigue (e.g., compromised movement control), which increases tissue loading

and ultimately increases the chance of injury [140]. Moderate acute loads coupled with low chronic loads, however, can also increase injury risk. The low chronic loads may lead to physical deconditioning, which reduces a bowler's capacity to withstand the application of the relatively moderate loads experienced in the acute period [140]. Pace bowlers may therefore benefit from avoiding spikes in load and should aim to achieve moderate chronic loads.

To ensure bowlers avoid these spikes and achieve moderate chronic loads, they should record and monitor the number of balls they bowl, the number of bowling sessions per week, their internal load and their ACWR for both balls bowled and internal load. There are a variety of methods available for recording and monitoring bowling load; however, each must be considered within the context of community-level cricket. Wearable technologies that utilise accelerometer, gyroscopic, magnetometer and global positioning system technologies are one available method for monitoring bowling load [70, 141]. Despite the ability of these technologies to objectively determine when a ball has been bowled, the cost associated with these devices may make them an unrealistic option for community-level bowlers. Smartphone applications and bowling logbooks, however, can be more cost-effective methods for monitoring load. While these approaches may be prone to recall bias [80], daily logbooks have been successfully used in the past to monitor external load in adolescent pace bowlers [26, 29].

Although logbooks can be successfully used to monitor a bowler's load, they require a certain level of 'buy-in' from the player involved. While in high-performance under-age programs this may not be an issue, at the community-level this method is less likely to result in valid load quantification. Consequently, the coach is typically responsible for ensuring their bowlers achieve appropriate bowling loads. It may be most practical for the coach to prescribe each player a certain number of balls/bowling sessions per week and ensure players adhere to these recommendations. If a bowler is playing for two teams (e.g., both club and school cricket teams), this should be considered when training loads are prescribed. Furthermore, coaches

should also consider the bowler's age when prescribing bowling load. Older adolescent individuals could potentially tolerate higher loads as they are typically stronger and have greater bone mass than younger adolescent individuals [142, 143]. To tolerate these higher loads the older adolescent bowlers would require a longer pre-season period to ensure they are adequately conditioned. With all this considered, caution should still be exercised when providing general recommendations to adolescent pace bowlers. This is especially important for those going through their growth spurt or in the early years after the growth spurt where bone stress injuries are common [79, 144]. Muscle strength and power generation increase markedly around the years of the growth spurt [143] and the newly developed musculoskeletal tissues in these young athletes require time to adapt to the resultant increases in tissue loading [79].

Recommendations for bowling load in youth pace bowlers have been recently published by Cricket Australia (Table 3.4) [145]. These recommendations indicate that bowlers should avoid >2 consecutive bowling days and >4 bowling days per week. Bowlers are also encouraged to have a light bowling week every 4–5 weeks (i.e., perform 50% of prescribed bowling load) and a week with no bowling every 10–12 weeks [145]. Although these guidelines will assist bowlers in achieving moderate absolute loads and reduce their chance of experiencing a spike in load, further steps could be taken. To avoid spikes in internal load, for example, coaches could reduce the training duration or reduce training intensity during the weeks in which multiple matches are scheduled (e.g., longer rest periods between deliveries or bowling off a shorter run-up). Coaches could also avoid spikes in internal load by gradually increasing the training load in the month preceding a demanding week. As previously mentioned, adolescent pace bowlers may benefit from avoiding an ACWR for balls bowled of $\geq 142\%$ [29]. If a bowler knew they would be required to bowl 30 overs in the first week of the season, they could aim to achieve an average weekly bowling load in the final 4 weeks of the preseason of at least 22 overs (ACWR of 136%) to ensure their ACWR remained below 142%.

Table 3.4 Bowling load recommendations for youth pace bowlers.

Age group	Under 11s	Under 13s	Under 15s	Under 17s	Under 19s
Maximum overs per spell [a]	2	4	5	6	7
Maximum overs per match	4	8	12	16	20
Target deliveries per week [b]	NS	100-120	100-120	120-150	150-180
Weeks of preseason [c]	NS	NS	4-6	6-8	8-10

Table adapted from Cricket Australia youth pace bowling guidelines, with permission [145], List of abbreviations, NS not specified. a work to rest ratio of 1:1 (e.g., the rest period after bowling a 4 over spell should equal 8 match overs), b both training and match deliveries combined, c gradually build-up bowling load over this time.

Although somewhat outside the scope of this section, it is also important to monitor and potentially manipulate throwing load. One study involving adult cricketers revealed that those who performed >75 throws per week were at a significantly greater risk of injury (RR = 1.73, 95% CI 1.03–2.92) than those who completed <75 throws [146]. Furthermore, in the week preceding an injury, a player's throwing load was approximately 36% higher than their average weekly throwing load [146]. These results may not translate directly to adolescent cricketers, but they highlight the need to consider throwing load. When working with adolescent pace bowlers, it is important to calculate ACWRs for balls thrown and use this information to avoid acute spikes in throwing load.

3.7 Conclusions

Adolescent pace bowlers are prone to sustaining non-contact injuries and could benefit from participating in the example program provided in this paper, which aims to increase muscular strength (external shoulder rotators, hamstrings and hip adductors), improve dynamic neuromuscular control of the lumbo-pelvic region/lower-limbs and increase trunk extensor muscle endurance. Cricketers in other positions are also likely to receive benefit from the example program and coaches should therefore ensure all players in the team perform the exercises if they are implemented. It should also be noted that additional empirical evidence is

needed to confirm the effectiveness of the example program. Coaches and bowlers should work to reduce excessive shoulder counter-rotation and lateral trunk flexion during the bowling action. Appropriate feedback will play a vital role when altering bowling biomechanics, and coaches should therefore carefully consider their approach when communicating with bowlers. Prescribing appropriate bowling loads is another key factor to consider. Bowlers should aim to establish moderate loads over the season and avoid large spikes in load. Ultimately, a multifactorial approach to injury prevention is needed to reduce injury risk in adolescent pace bowlers and should focus on modifying neuromuscular deficiencies, correcting poor bowling biomechanics and achieving appropriate bowling loads.

CHAPTER 4

EXERCISE-BASED INJURY PREVENTION FOR COMMUNITY-LEVEL ADOLESCENT CRICKET PACE BOWLERS: A CLUSTER-RANDOMISED CONTROLLED TRIAL

The investigations in Chapters 4 and 5 commenced before Chapter 3 had been published. The exercise-based IPP in Chapter 3 (Appendix D), which was amended in accordance with reviewer feedback, therefore differs slightly to the program implemented in Chapters 4 and 5. Importantly, only the trunk extensor endurance exercises differ between Chapters 4/5 and Chapter 3. The trunk extensor endurance exercises included in Chapters 4 and 5 are presented in Appendix E.

4.1 Abstract

Objectives: To investigate if an exercise-based IPP can modify risk factors for injury in community-level adolescent cricket pace bowlers. *Design:* Cluster-randomised controlled trial. *Methods:* Eight cricket organisations (training two times per week and no previous involvement in a structured IPP) participated in this cluster-randomised trial. Participants were aged 14 to 17 years, injury free, and not currently performing a rehabilitation/exercise program. Cricket organisations (clusters) were block-randomised by computerised number generation into an intervention group (n=32 performed an eight-week IPP at training) or control group (n=33 continued their usual cricket activity). Participants were not blinded to group allocation. Strength, endurance, and neuromuscular control were assessed at baseline and follow-up. Treatment effects were estimated using linear mixed models. *Results:* Sixty-five male adolescent pace bowlers (intervention n=32 and control n=33) were randomised. There were significant treatment effects favouring the intervention group for shoulder strength (90°/s) 0.05 (95% CI 0.02-0.09) Newton meters per kilogram body weight (N.m/kg), hamstring strength (60°/s) 0.32 (95% CI 0.13-0.50) N.m/kg, hip adductor strength dominant 0.40 (95% CI 0.26-0.55) N.m/kg and non-dominant 0.33 (95% CI 0.20-0.47) N.m/kg, SEBT reach distance dominant 3.80 (95% CI 1.63-6.04) percent of leg length (%LL) and non-dominant 3.60 (95% CI 1.43-5.78) %LL, and back endurance 20.4 (95% CI 4.80-36.0) seconds. No differences were observed for shoulder strength (180°/s) (p=0.09), hamstring strength (180°/s) (p=0.07), lumbo-pelvic stability (p=0.90), and single leg squat knee valgus angle (dominant p=0.06, non-dominant p=0.15). *Conclusions:* Exercise-based IPPs can modify risk factors for injury in community-level adolescent pace bowlers. Future research is needed to confirm if IPPs can also reduce injury risk in this population.

4.2 Introduction

Cricket is a popular community-level sport in many Commonwealth countries, though it is associated with a risk of injury [13]. Pace bowlers are the most injury-prone group in youth cricket, with seasonal incidence rates of approximately 26% [13]. Most of their injuries are non-contact and generally to the low back, shoulder and lower-limb [13]. Lumbar stress fractures are the most concerning injury in youth pace bowlers (one-year incidence 12%) and typically cause players to miss several months of cricket [31].

A number of risk factors for these injuries have been identified in Chapter 2 and these include; poor bowling biomechanics, inappropriate bowling load, and neuromuscular deficiencies (e.g., reduced muscular strength, neuromuscular control, and muscular endurance) [80]. While earlier studies have attempted to change bowling biomechanics [81] and there are published guidelines for bowling load [145], there is minimal published literature which has attempted to alleviate injury risk factors by modifying neuromuscular deficiencies in youth pace bowlers.

Research from other sports such as soccer, baseball, and gymnastics, indicates that exercise-based IPPs can improve strength, increase neuromuscular control, and improve endurance [94, 105, 147, 148]. Several IPPs have also been successfully developed for community athletes and when implemented properly, these programs can reduce injury risk by approximately 32% [20]. Despite the success of these programs, the efficacy of exercise-based injury prevention has not been examined in cricket. Therefore, this study aimed to investigate if the exercise-based IPP developed in Chapter 3 can modify neuromuscular risk factors in community-level adolescent pace bowlers.

4.3 Methods

This prospective cluster-randomised control trial was registered retrospectively during the recruitment phase (ACTRN12616001572459) and reported in accordance with both the Consolidated Standards of Reporting Trials (CONSORT) framework for cluster-randomised trials [149] and the Consensus on Exercise Reporting Template [150]. Eight cricket organisations represented the clusters in this investigation. Four organisations were randomised into an intervention group that performed a structured IPP over an eight-week period. Four other organisations were randomised into a control group that continued their normal cricket activity. Either side of the eight-week intervention period, all players attended a baseline and a follow-up testing session.

Participants were recruited from cricket organisations (cricket schools and cricket clubs) within proximity of the testing venue. Eligibility criteria for the clusters included; training two times per week and no current or previous involvement in a structured IPP. When recruiting from cricket schools, the players in the first and second XI teams were eligible. When recruiting from cricket clubs, the players from the Under 15s and Under 17s teams were eligible. Further eligibility criteria for participants included; aged 14-17 years, identified by their coach as a pace bowler, currently injury free, and not involved in any rehabilitation/structured IPP. Prior to randomisation, consent was obtained from the coordinator of each organisation, the cricket coaches, participants, and the participant's parent/guardian. During this process, all entities were informed about potential assignment into either group and blinding of group allocation was therefore not achieved. Ethics approval was obtained from the institution's human research ethics committee (2016/136).

This investigation was conducted in four waves across two seasons (2016/17 and 2017/18). In each testing wave, two cricket organisations, matched for type (i.e., club or school), were block-randomised by computerised number generation into either an intervention or

control group. The researcher overseeing the randomisation process was not involved in the recruitment process and group allocation was concealed from the recruiting researcher until after baseline testing.

The IPP used in this study was based on that described in Chapter 3 [151]. The program was developed to prevent injuries in the shoulder, low back, hip adductors, hamstring, knee and ankle [151]. Players in the intervention group performed this program twice per week over an eight-week period (16 sessions total). All sessions were performed on a grassed cricket oval with groups of 6 to 12 players. Each session was performed before cricket training in place of the normal warm-up, took approximately 10-15 minutes to complete, and required limited equipment (i.e., only cricket balls and resistance-bands). While the current exercise program was designed to be implemented by a cricket coach [151], to assess program effectiveness in ideal conditions, as per the TRIPP framework [23], an Accredited Exercise Physiologist with three years of experience delivered all exercise sessions.

Three progressive phases were included in the program, with all players beginning in phase one and progressing as a group from thereon. Six exercise components were completed per session; (a) dynamic warm-up, (b) shoulder external rotation strengthening, (c) hip adductor strengthening, (d) hamstring strengthening, (e) lumbo-pelvic/lower-limb dynamic neuromuscular control, and (f) trunk extensor endurance. The trunk extensor endurance exercises in the current chapter (Appendix E) differ to those presented in Chapter 3 [151].

General encouragement was provided to the participants during the exercise sessions, but no additional motivation strategies were used. Players in the intervention group were asked to report if any adverse events occurred during the exercise program. If necessary, the intervention was adapted to avoid the recurrence of an adverse event. The cricket organisations in the control group were monitored throughout the intervention and did not perform any

structured IPP. At the completion of the study all players in the control group were given access to the IPP.

All testing sessions were conducted in a biomechanics laboratory. Participant age, height and weight were collected before players completed a ten-minute aerobic warm-up. Measures of external shoulder rotator strength, hamstring strength, hip adductor strength, lumbo-pelvic stability, composite reach distance on the SEBT, single leg squat knee valgus angle, and back endurance test were then collected. The outcome assessor was blind to group allocation at baseline, but not blinded during the intervention period and follow-up.

Eccentric isokinetic strength for the dominant shoulder rotators and non-dominant hamstring was assessed using a Humac Norm dynamometer (CSMi, Stoughton, MA). Shoulder strength was assessed at 90°/s and 180°/s through full pain-free range of motion. The participant lay supine with the shoulder abducted to 90° and elbow flexed to 90° with the procedure showing acceptable test-retest reliability (intraclass correlation coefficient (ICC)=0.76) [152]. Hamstring testing was performed seated at 60°/s and 180°/s through full pain-free range of motion with high reliability previously reported (ICC=0.94) [153]. Participants performed five consecutive familiarisation repetitions and then five consecutive test repetitions. A one-minute rest was given after the familiarisation and testing repetitions. The highest peak torque value from each testing speed was recorded in N.m/kg.

Isometric hip adductor strength was tested with a handheld dynamometer (Lafayette Instruments, Lafayette, USA) using standard testing procedures which have shown excellent reliability (ICC=0.89) [154]. Participants were tested in the supine position and performed three trials on each leg [154]. Weight-normalised torque (N.m/kg) was calculated using maximal force and leg length.

A five-stage lumbo-pelvic stability test was performed using procedures outlined previously [155]. Participants were required to maintain pressure on a cuff that was placed

under the lumbar spine (Stabilizer Pressure Biofeedback Unit, Chattanooga Group Inc, USA) while performing a series of leg movements. Two attempts were given per stage and the highest successfully completed stage was recorded.

During the SEBT participants were required to reach as far as possible in the anterior, posterior-medial, and posterior-lateral directions, as per standard procedures (high reliability has been reported for this test, ICC=0.89-0.93 [113]. Participants performed six familiarisation reaches and then three test reaches on each leg in each direction. Reach distance was measured with 3D Qualisys Motion Capture (QTM) and normalised to leg length. A composite reach distance was calculated for the dominant and non-dominant leg.

Maximal knee valgus angle during the eccentric phase of the single leg squat was measured from the stance leg using QTM. All squats were performed on a 25° decline box. Retro-reflective markers were placed on the body based on a custom marker set [125]. Markers were also placed on all malleoli and femoral condyles for static subject calibration trials. Dynamic functional methods were used to locate knee and hip joint centres [156]. Participants performed two familiarisation trials on each leg, and after a one-minute rest, performed five test squats on each leg. Data analysis was performed using Visual 3D (Version 5, C-Motion, Germantown, USA). All data were filtered using a 6Hz Low pass Butterworth Filter. Joint angles were calculated using a standard joint coordinate system [157].

Maximal hold time (seconds) on the Biering-Sorensen test was used to assess back endurance. Reliability for this test has been reported as moderate (ICC=0.59) [158]. A digital inclinometer (Dualer IQ Inclinometer J-Tech Medical, Salt Lake City, UT) was also placed on the upper back to measure trunk angle. The test was stopped if participants dropped the trunk by ≥10º below horizontal.

During the intervention period training attendance was recorded from both groups as a percentage of total cricket training sessions (16 sessions attended = 100% attendance). Exercise

session attendance was recorded in the same manner, however, only for those in the intervention group. Exercise compliance was again only recorded in the intervention group and reported as a percentage of completed exercise components per session (all exercise components completed at every session attended = 100% compliance). Players who were absent from training received a 'not applicable' for exercise program compliance on that particular day.

Fifteen minutes after each training session in the current study, all participants reported their sessional RPE (using a using a 0-10 category ratio scale). All participants also reported their bowling load (average number of balls bowled per week). This was collected for all bowling sessions and therefore considered balls delivered during any training session, match, or casual bowling session. Players recorded their bowling load in a logbook and the primary researcher met with each player weekly to ensure these were regularly updated.

Cohen's f effect sizes were calculated for each of the primary outcomes using smallest detectable difference values. The smallest Cohen's f effect size (0.247) was then input into G*Power (3.1.9.2) to produce a sample estimate of n=36 (α error probability at 0.05 and β error probability at 0.80). To account for clustering a variance inflation factor of 1.7 was calculated using an average cluster size of n=8 and an intra-cluster correlation coefficient of 0.1 [159]. The final required sample was n=62.

Statistical analyses were performed using IBM SPSS Statistics V.24. Treatment effects (95% CI) were estimated with linear mixed models, in line with the intention-to-treat principal. Follow-up scores were input as the dependant variable and adjusted for baseline score and cluster. Cohen's *d* effect sizes were calculated with the average standard deviation at follow-up and the treatment effect. The intra-cluster correlation coefficient for each variable at baseline was calculated with a one-way analysis of variance (ANOVA). Between group-differences for training session attendance, training session RPE, and bowling load were examined with independent-samples t-tests. Statistical significance was set at <0.05.

4.4 Results

Participant recruitment and flow through the study is presented in Figure 4.1. The intervention was delivered as planned. Exercise session attendance for the intervention group was 83.1±12.1% and exercise compliance was 98.8±3.1%. Two players reported delayed onset muscle soreness in the hamstrings after the first week and two players also experienced back pain while performing the stage two trunk extensor endurance exercise. Further investigation revealed that these players had initially hurt their back while bowling and the stage two exercise was reproducing this pain. These players reverted to the stage one trunk extensor endurance exercise (which did not cause them pain) for the remainder of the program. Baseline player demographic information and values for training session attendance, training session RPE, and bowling load are presented in Table 4.1.

There were significant treatment effects (95% CI) in favour of the intervention group for shoulder strength (90°/s) (0.05 N.m/kg; 0.02 to 0.09), hamstring strength (60°/s) (0.32 N.m/kg; 0.13 to 0.50), hip adductor strength dominant side (0.40 N.m/kg; 0.26 to 0.55) and non-dominant side (0.33 N.m/kg; 0.20 to 0.47), SEBT reach distance dominant side (3.80 %LL; 1.63 to 6.04) and non-dominant side (3.60 %LL; 1.43 to 5.78), and back endurance (20.4 seconds; 4.80 to 36.0) (Table 4.2).

Table 4.1 Demographics and anthropometrics at baseline, attendance, and player load.

	Intervention n=32	Control n=33	*P* value
Age (years)	15.8 ± 1.0	15.4 ± 1.2	-
Height (cm)	180.3 ± 7.1	175.7 ± 8.2	-
Weight (kg)	69.4 ± 11.5	63.8 ± 10.4	-
Training session attendance (%)	86.4 ± 9.5	86.9 ± 13.0	0.88*
Average training session RPE (0-10)	5.3 ± 0.9	6.2 ± 1.0	0.01*
Mean overs per week	16.0 ± 5.4	19.7 ± 7.7	0.03*

*Values presented as mean (±) standard deviation, *statistically significant (p<0.05).*
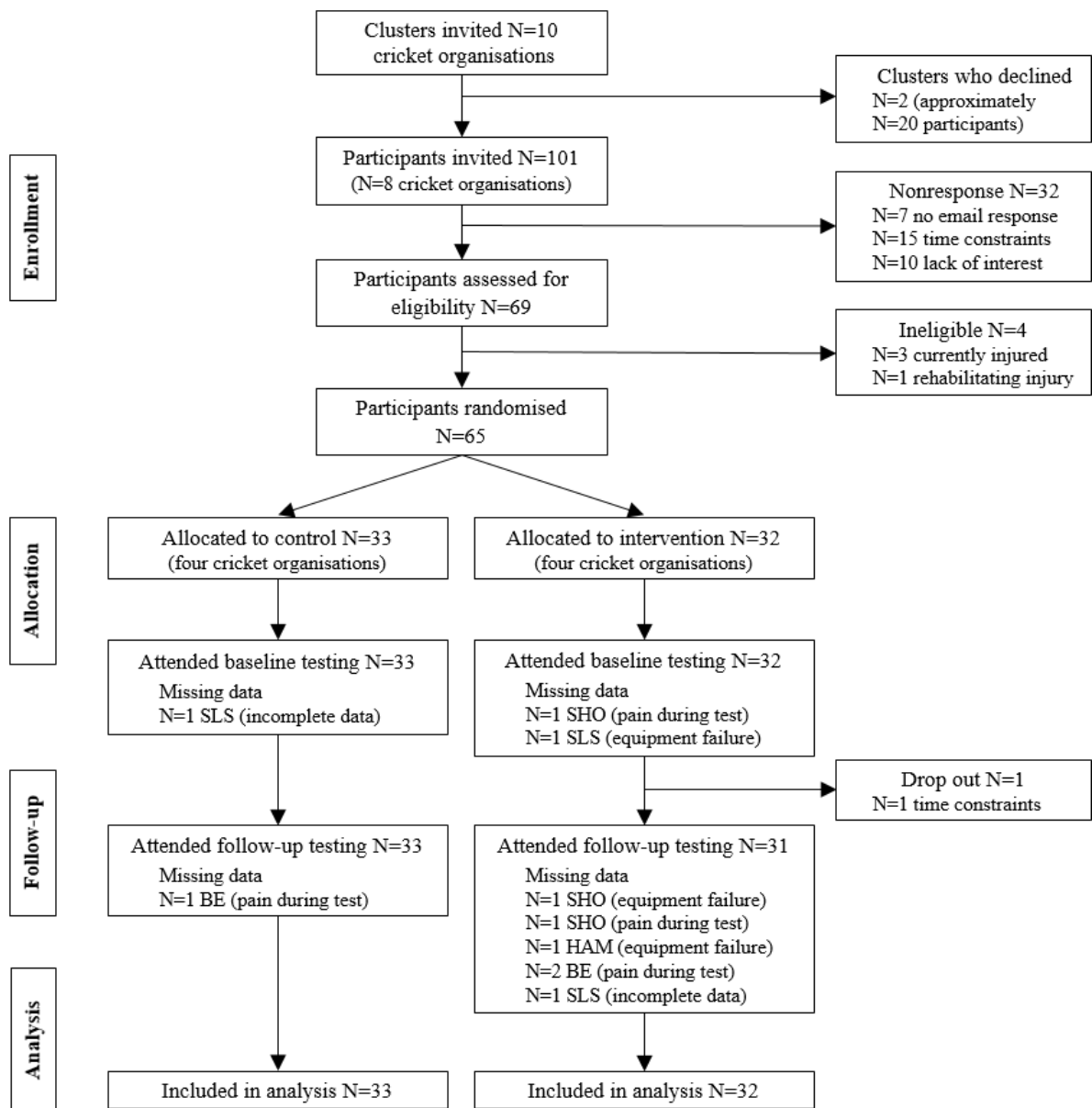
BE back endurance test, SHO shoulder strength tests, HAM hamstring strength tests, SLS single leg squat test

Figure 4.1 Flow of participants through Chapter 4.

4.5 Discussion

The exercise-based IPP used in this study improved hip adductor strength, increased reach distance on the SEBT, and improved back endurance. Significant improvements in shoulder and hamstring strength were also observed at the slower isokinetic testing speeds. When comparing the current results to other studies, there are similar, albeit slightly smaller improvements in most outcomes [94, 105, 147, 148]. This may have occurred because the study

Table 4.2 Outcome results and treatment effects Chapter 4.

Outcome	Intervention n=32	Control n=33	Treatment effect	Cohen's d	ICC
Shoulder strength 90°/s					
Baseline	0.52 ± 0.10	0.54 ± 0.10			
Follow-up	0.55 ± 0.09	0.52 ± 0.09	0.05 (0.02-0.09)*	0.56	0.07
Shoulder strength 180°/s					
Baseline	0.54 ± 0.10	0.56 ± 0.08			
Follow-up	0.55 ± 0.09	0.53 ± 0.09	0.03 (-0.01-0.07)	0.33	0.04
Hamstring strength 60°/s					
Baseline	1.96 ± 0.46	2.04 ± 0.50			
Follow-up	2.22 ± 0.54	1.99 ± 0.45	0.32 (0.13-0.50)*	0.65	0.17
Hamstring strength 180°/s					
Baseline	2.06 ± 0.50	2.09 ± 0.55			
Follow-up	2.27 ± 0.54	2.13 ± 0.52	0.18 (-0.01-0.38)	0.34	0.09
Hip adductor strength D					
Baseline	1.65 ± 0.38	1.83 ± 0.46			
Follow-up	1.97 ± 0.36	1.70 ± 0.42	0.40 (0.26-0.55)*	1.03	0.18
Hip adductor strength ND					
Baseline	1.62 ± 0.42	1.86 ± 0.49			
Follow-up	1.90 ± 0.37	1.75 ± 0.45	0.33 (0.20-0.47)*	0.80	0.16
SEBT reach distance D					
Baseline	80.93 ± 6.92	81.19 ± 7.92			
Follow-up	83.17 ± 7.06	79.16 ± 8.25	3.80 (1.63-6.04)*	0.50	0.28
SEBT reach distance ND					
Baseline	80.87 ± 6.68	80.04 ± 7.69			
Follow-up	82.67 ± 6.62	78.61 ± 7.76	3.60 (1.43-5.78)*	0.50	0.33
SLS knee valgus angle D					
Baseline	6.12 ± 3.47	5.94 ± 3.32			
Follow-up	5.75 ± 3.47	6.17 ± 3.98	-1.17 (-2.37-0.04)	0.31	0.14
SLS knee valgus angle ND					
Baseline	4.56 ± 5.67	5.66 ± 3.51			
Follow-up	4.51 ± 3.89	5.92 ± 4.65	-1.22 (-2.91-0.47)	0.29	0.11
Lumbo-pelvic stability score					
Baseline	1.48 ± 0.89	1.88 ± 1.45			
Follow-up	1.77 ± 1.19	2.24 ± 1.54	0.40 (-0.56-0.64)	0.03	0.07
Back endurance					
Baseline	139.3 ± 41.7	166.2 ± 55.7			
Follow-up	155.4 ± 45.9	155.6 ± 56.0	20.4 (4.80-36.0)*	0.40	0.12

Baseline and follow-up outcome scores presented as mean (±) standard deviation, Treatment effects (95%CI) were adjusted for baseline score and cluster, ICC intra-cluster correlation coefficient at baseline, SEBT star excursion balance test, SLS single leg squat, D dominant side, ND non-dominant side, Strength (N.m/kg), SEBT (%LL), SLS (°), lumbo-pelvic stability (stage), back endurance (sec), * statistically significant (p<0.05).

populations differed (e.g., different gender [147, 148], playing-level [105], or sport [94, 105, 147, 148]) or due to slight differences in the way outcomes were assessed. It is also possible that the other studies were more effective because they targeted one risk factor/injury in their exercise program. In the current study a broader approach was taken (i.e., multiple risk factors were targeted) and as a result, the exercise volume was comparatively lower for each prescribed exercise. Despite this, multifaceted exercise programs which can be incorporated into training are favoured in a practical setting where coaches and players typically do not have enough time to implement multiple stand-alone IPPs [160].

While injury risk was not assessed in the current investigation, results from other studies can provide some insight into the clinical importance of the findings. In handball players for example, shoulder injury-risk reduced by around 30% for every 10 N.m increase in external rotator strength [89]. When extrapolating this finding to the results in the current study, the approximate 3 N.m increase in the intervention group's peak torque (measured at 90°/s) may represent an approximate 9% reduction in injury risk. It should be acknowledged, however, that the relationship between muscle strength and injury risk may not be linear, and future research is needed to confirm if this 3 N.m increase in peak torque protects against shoulder injury. The improvements in the intervention group's SEBT reach distance (approximately 3.6-3.8 %LL) may also be clinically important. In adult pace bowlers for example, reduced reach distance on the SEBT test (3.0-3.6 %LL) was identified as a risk factor for lower-limb/low back injury [161]. It is also likely that the improvements in the intervention group's hip adductor strength and hamstring strength are capable of attenuating the risk of groin injury and hamstring strain. In studies involving soccer players where the Copenhagen adduction exercise and the Nordic hamstring exercise have been prescribed, the risk of groin injury and hamstring strain reduced by approximately 40% [162] and 70% [116], respectively. While the mechanism of injury may

differ in soccer and cricket, and future research is needed in this area, the Copenhagen adduction exercise and the Nordic hamstring exercise may still protect against injury in cricket players.

The non-significant findings for shoulder and hamstring strength (180º/s) may be related to exercise specificity as the training speeds for the exercises targeting these factors were slower than the 180º/s testing speed. Developing field-based strategies to improve strength at functionally appropriate speeds may be beneficial for future studies. The null finding for lumbo-pelvic stability is somewhat expected as the training protocol did not specifically target the abdominal muscles. Despite this, both groups still improved their lumbo-pelvic stability by approximately 16% which may suggest a learning effect occurred after the baseline testing session. It is also important to note that the lumbo-pelvic stability test utilised in the current study may be unreliable and potentially lack the precision to detect differences between the groups. In a previous study which investigated a comparable lumbo-pelvic stability test for example, only a moderate reliability score was reported (ICC=0.65) [163].

The non-significant result for single leg squat knee valgus angle may reflect the lack of visual feedback provided to the athletes during the exercise sessions. In previous research, the use of appropriate visual and verbal feedback is identified as an important factor [164]. Although a pragmatic approach was taken to reflect the context of implementation, where a coach is typically unable able to provide visual feedback to all athletes during all exercises, my results indicate that visual feedback may be needed to alter squat mechanics in pace bowlers.

Further investigation into the bowling load data revealed that the additional overs in the control group primary came from match deliveries. The bowlers in the control group may therefore have rated their training sessions as more intense because they had bowled more match overs in the days previous. Most exercise sessions in the current study were missed because players were absent from training (52% of all missed sessions) or because training sessions were cancelled due to rain (31% of all missed sessions). It is important to note, that

two players missed an exercise session (2.5% of all missed sessions) because their coach instructed them to perform skills training instead. This is an important finding as it highlights a potential barrier to real-world program implementation where the coach may prioritise skills training over performing the exercise program. Future work in this area could therefore benefit from investigating if the current IPP also improves bowling performance.

An important finding in the current study was the general decline in most outcomes at follow-up for those in the control group. In previous work at the elite-level, it has been suggested that the physical demands of cricket are not adequate to maintain pre-season values of strength and power [165]. The findings in the current paper appear to support these claims among community-level cricketers and highlight the importance of continued exercise-based injury prevention throughout the season. Despite this, it should be acknowledged that those in the control group decreased at follow-up because they knew they had been placed into a non-exercise group [166]. It is also important to note that the outcome assessor was not blinded to group allocation at follow-up.

There is also the possibility of contamination (diffusion of treatment) between the two groups. The control group was monitored throughout the intervention and did not perform any structured exercise-based IPP at training. Players in the control group, however, could have performed an exercise-based IPP outside of training. Regardless, contamination of this nature would likely result in an underestimation of the treatment effect in the current paper.

To ensure the exercise were performed correctly, an Accredited Exercise Physiologist delivered the program to all players. While this allowed training to be performed under somewhat ideal conditions, it did not allow us to assess program adherence in a practical setting, where the coach typically delivers the exercises. Having an Accredited Exercise Physiologist deliver the program may also explain why the compliance levels were so high in the current study. Due to season scheduling, only an eight-week exercise program (16 sessions) was

implemented. If the current exercise program was performed over the entire season, as might be the case in a real-world setting, the intervention may have been more effective.

4.6 Conclusions

This study shows that exercise-based IPPs improve shoulder and hamstring strength (when measured at slow isokinetic speeds), increase hip adductor strength, improve SEBT performance, and increase trunk endurance. The modification of these factors could also protect against injury in community-level adolescent pace bowlers. Although these findings are promising, future prospective investigations are needed to confirm if exercise interventions can not only modify risk factors, but also reduce injury risk in community-level pace bowlers. This is especially important in a cricket-context where other risk factors, such as poor bowling biomechanics and inappropriate bowling loads also influence injury risk.

CHAPTER 5

MODIFYING BOWLING KINEMATICS IN CRICKET PACE BOWLERS WITH EXERCISE-BASED INJURY PREVENTION: A CLUSTER-RANDOMISED CONTROLLED TRIAL

Thus far, this thesis has provided prevention strategies for several common injuries. However, as most biomechanical risk factors in pace bowlers pertain to the back, the current chapter has a specific emphasis on this area. It is also important to highlight that one participant from Chapter 4 was not able not partake in Chapter 5. This occurred because the participant was not medically cleared to bowl but was able to perform the assessments in Chapter 4.

5.1 Abstract

Objectives: Undesirable bowling kinematics can increase the risk of low back injury. This study investigated if an exercise-based injury prevention program (IPP) could modify bowling kinematics in community-level adolescent pace bowlers. *Design:* Cluster-randomised controlled trial. *Methods:* Pace bowlers from eight cricket organisations were cluster-randomised into an intervention (n=31) or control group (n=33). At baseline and follow-up sessions biomechanical bowling data were collected. Between sessions, the intervention group completed an eight-week IPP while the control continued their normal cricket activity. Treatment effects (95% CI) were estimated with linear mixed models. *Results:* There were significant treatment effects favouring the intervention group for shoulder counter-rotation (-3.8°; -7.2° to -0.3°) and lateral trunk flexion relative to the pelvis (-2.2°; -4.0° to -0.5°). Shoulder counter-rotation also increased in the control group by 2.2° (Cohen's $d = 0.22$). There were no effects of the intervention on: lateral trunk flexion at front foot contact (FFC) (1.2°; -2.5° to 4.8°), lateral trunk flexion at ball release (BR) (-0.5°; -3.0° to 2.0°), pelvis rotation at FFC (0.9°; -4.0° to 2.2°), pelvis rotation at BR (-1.1°; -5.7° to 3.6°), front hip angle at FFC (1.6°; -3.6° to 6.7°), front hip angle at BR (-1.6°; -5.0° to 1.9°), front knee angle at FFC (-1.1°; -4.5° to 2.3°), front knee angle at BR (1.7°; -5.6° to 9.1°), or ball velocity (1.1 km·h^{-1}; -7.5 km·h^{-1} to 9.7 km·h^{-1}) *Conclusions:* The IPP maintained shoulder counter-rotation and lateral trunk flexion relative to the pelvis in the intervention group and this could attenuate injury risk. No treatment effects were observed for lower-limb kinematics.

5.2 Introduction

Cricket is a popular sport in many countries and provides young people with an opportunity to increase physical activity. There is however a risk of injury associated with playing cricket. Seasonal incidence rates in youth cricket are between 114-242 injuries/1000 participants, which are comparable to those seen in other team sports such as soccer (107 injuries/1000 participants) [11, 12]. Most injuries in youth cricket affect pace bowlers and within this group, approximately 37-47% of all injuries are to the low back [13, 25]. Lumbar stress fractures are one of the most common injuries in this region and have a four-year incidence of 24% [32]. Lumbar stress fractures are also relatively severe and can cause between 6-12 months of missed cricket [32].

Risk factors for lumbar injury in community-level pace bowlers, which could be potential targets for modification, fit into three broad categories: neuromuscular deficiencies, bowling workload, and bowling biomechanics (i.e., >30° shoulder counter-rotation, excessive lateral trunk flexion, excessive movements of the pelvis, and bowling with a straighter front lower-limb) [31, 52, 62, 80]. In Chapter 4 I demonstrated that an exercise-based IPP designed to modify neuromuscular risk factors can significantly improve muscle strength, neuromuscular control, and muscle endurance in community-level pace bowlers [167]. Cricket Australia has also published guidelines to help youth pace bowlers achieve appropriate age-specific bowling loads [168]. There is however, limited evidence for interventions that have successfully modified bowling biomechanics in community-level adolescent pace bowlers.

Evidence suggests that bowling kinematics do not naturally change over the course of a season and specialised interventions may therefore be needed to alter biomechanics [81]. In an investigation by Elliott et al.[169], reducing the length of the pitch significantly decreased shoulder counter-rotation in junior bowlers (under 11s and under 13s), but not in older adolescent bowlers (under 15s). Attempts to reduce shoulder counter-rotation with the use of a specialised bowling harness have also been unsuccessful [132]. At the elite level beneficial

modifications to shoulder counter-rotation have been reported, although these interventions were guided by 3D biomechanical analysis and involved specific bowling technique training prescribed by elite coaching staff or experienced biomechanists [52, 81]. At the community-level, where access to biomechanical testing facilities is limited and coaches may be inexperienced, this approach has clear limitations [151].

In other community-level sports, kinematics of the trunk, hip and knee have been modified with exercise based IPP; and this approach could therefore present as a viable option for modifying kinematics in pace bowlers [170]. Exercise-based IPPs, which can be delivered by a relatively inexperienced coach and implemented without expensive equipment, could also present as a viable option for modifying kinematics in community-level pace bowlers [21]. The current study therefore investigated if an eight-week exercise-based IPP, originally designed to modify neuromuscular risk factors, could also change bowling kinematics in community-level adolescent pace bowlers.

5.3 Methods

This parallel cluster-randomised controlled trial was reported in accordance with both the CONSORT framework for cluster-randomised trials [149] and the Consensus on Exercise Reporting Template [150]. The methods outlined in this study have been detailed in Chapter 4 [167]. Eight cricket clubs or schools (clusters) were randomly assigned to receive an eight-week exercise-based IPP or a control intervention. Those in the intervention group continued their usual cricket activity during the intervention period (i.e., two training sessions and one match per week), however instead of performing their usual warm-up at training, they completed an exercise-based IPP (two sessions per week for eight weeks = 16 total sessions). Those in the control group continued their usual cricket activity and therefore performed their standard warm-up before training. The standard warmup typically included a five-minute jog and a series

of stretches for the upper-limb, trunk, and lower-limb. Within a two-week period before and after the eight-week intervention, all players attended a biomechanics laboratory for baseline and follow-up assessment of their bowling kinematics.

Eligible schools and clubs were required to have organised training sessions two times per week and no previous involvement with a structured IPP. Eligible pace bowlers were aged 14-17 years, currently injury free, and not involved in a rehabilitation/structured IPP. Ethics approval was obtained from the Murdoch University's Human Research Ethics Committee (2016/136) and consent was obtained from all entities involved (i.e., the coordinator of each cricket organisation, the cricket coaches, participants, and the participant's parent/guardian). Blinding of the participants was not appropriate for this research, as players were either required to complete an exercise-based IPP across the intervention period, or simply train as normal.

This study was conducted in four waves across the 2016/17 and 2017/18 seasons. The eight cricket organisations were matched for type (i.e., club or school) and then block-randomised by computerised number generation into either an intervention group or a control group. Allocation was concealed from the recruiting researcher until after baseline testing and the researcher overseeing randomisation was not involved with recruitment.

The intervention group performed the IPP on a grass cricket oval with groups of 6 to 12 players. Each session took approximately 10-15 minutes to complete and only required the use of cricket balls and resistance-bands. Although the exercise program was designed to be delivered by a cricket coach [151], an Accredited Exercise Physiologist with three years of experience delivered all exercise sessions in the current study. This approach was taken to allow the program effectiveness to be assessed in ideal conditions as per stage three of the Translating Research into Injury Prevention Practice framework [23].

Details of the exercise program used in this study have been presented in Chapter 4 [167]. In brief, six exercise components were completed per session: (1) dynamic warm-up, (2)

strengthening of the shoulder external rotators, (3) hip adductor strengthening, (4) hamstring strengthening, (5) dynamic neuromuscular control of the lumbo-pelvic region and lower-limb and, (6) trunk extensor endurance. The researchers provided verbal feedback to the participants during the injury prevention program but did not provide any specific coaching instruction to correct bowling technique. The verbal feedback was largely focused on ensuring correct and safe exercise technique, and therefore included cues to reduce excessive knee valgus angles and excessive movements of the trunk/pelvis. All cues provided to the players during the exercise session were taken directly from the IPP program manual, which has been published as supplementary material in a previous study [151]. The primary researcher took this approach to help mimic the context of implementation, where an inexperienced coach may read directly off the program manual when providing feedback.

At baseline and follow-up testing sessions participants firstly completed a 10-minute self-directed warm-up. Following this, all players performed a series of neuromuscular assessments as previously presented [167]. Retro-reflective markers were then placed on various anatomical landmarks according to a custom marker set [125, 171, 172]. Markers were also placed on the medial and lateral malleoli and the medial and lateral femoral condyles for static subject calibration trials. An additional retro-reflective marker was placed on a 156g cricket ball to measure ball velocity. After bowling three practise deliveries, each participant was instructed to bowl six legal deliveries at match intensity. A target was placed directly behind the wickets at the striker's end to simulate an appropriate bowling area. Deliveries which missed the target were not included in the analysis. All bowling deliveries took place on a synthetic, standard length cricket wicket within a biomechanics laboratory. The laboratory was large enough for bowlers to perform off their full run-up and follow-through as they normally would. Marker trajectories were tracked using a 12-camera motion capture system (Oqus3+ cameras (Qualisys AB, Gothenburg, Sweden), Qualisys Track Manager software). A one-

minute rest was required between deliveries because of data processing. The three best deliveries for each participant were used for analysis (maximal ball velocity with minimal marker loss).

Kinematic data analysis was performed using Visual 3D software (Version 5, C-Motion, Germantown, USA). Kinematic data were firstly filtered using a 15Hz low pass Butterworth filter. Dynamic functional methods were then used to locate knee and hip joint centres [173] and joint angles were calculated using a standard joint coordinate system [157]. Kinematics which have been established as risk factors for lumbar injury in pace bowlers were then identified during each delivery [31, 52, 62]. In the trunk these included; shoulder counter rotation, lateral trunk flexion at front foot contact (FFC), lateral trunk flexion at ball release (BR), and maximal lateral trunk flexion relative to the pelvis between FFC-BR (hereafter referred to as relative lateral trunk flexion). Lateral trunk flexion angles towards the non-dominant side were defined as positive. In the lower limb, pelvis rotation angle, front hip angle, and front knee angle were measured at FFC and BR. Positive angles for the hip and knee indicated flexion. As for the pelvis, 270° represented a front-on alignment. The timing of BFC and FFC were determined using force plate data (9287C Kistler Group Winterthur, Switzerland) and BR was considered as the first frame after the ball had left the hand.

During the intervention period, all players reported their sessional rating of perceived exertion (RPE) using a 0-10 category ratio scale fifteen minutes after each training session. The players were also required to record their bowling load in a logbook (number of balls bowled per day). The primary researcher met with each player on a weekly basis to ensure their logbooks were kept up to date. Cricket training attendance was also recorded from both groups as a percentage of total cricket training sessions (16 sessions attended = 100% attendance).

Exercise session attendance was recorded in the intervention group only (16 exercise sessions attended = 100% exercise attendance). Exercise compliance was also collected in the

intervention group (all exercise components completed at every exercise session attended = 100% exercise compliance). Players who were absent from training received a 'not applicable' for exercise compliance on that particular day.

The sample size estimate in this study, which has been described in detail in Chapter 4, was performed to detect a Cohen's f effect size of 0.25. The current study therefore had sufficient power to detect an approximate 6° change in shoulder counter-rotation between groups. In line with the intention-to-treat principle, treatment effects (95% CI) were estimated with linear mixed models (IBM SPSS Statistics V.24). Follow-up scores were input as the dependant variable and adjusted for baseline score (covariate) and cluster (random effect). Cohen's d effect sizes were also calculated where appropriate using the treatment effect and average standard deviation at follow up. The intra-cluster correlation coefficient was also calculated for each variable at baseline by dividing the between-cluster variability by the sum of the within-cluster and between-cluster variabilities [174].

5.4 Results

Details of recruitment, group allocation, participant drop out and missing data are reported in Figure 5.1. Missing kinematic data occurred when biomechanical markers were obstructed or fell off while bowling. It is important to note that all players with missing kinematic data recorded at least one testing session with complete data. For example, the two players in the intervention group with missing trunk kinematics at baseline, had complete data for trunk kinematics at follow-up. Baseline player demographic information, attendance and player load data are presented in Table 5.1. All players in this study were male. Exercise session attendance for the intervention group was $82.7 \pm 12.1\%$ and exercise compliance was $98.7 \pm 3.1\%$.

Table 5.1 Demographics and anthropometrics at baseline, attendance, and player load.

	Intervention n=31	Control n=33	P value
Age (years)	15.8 ± 1.0	15.4 ± 1.2	
Height (cm)	180.4 ± 7.2	175.7 ± 8.2	
Weight (kg)	69.7 ± 11.5	63.8 ± 10.4	
BMI	21.3 ± 2.7	20.6 ± 2.2	
Training session attendance	86.3 ± 9.6	86.9 ± 12.9	0.82
Average training session RPE	5.3 ± 0.9	6.2 ± 1.0	0.01*
Mean overs per week	16.2 ± 5.4	19.7 ± 7.7	0.04*

*Values presented as mean (±) standard deviation, BMI body mass index, * Statistically significant (p < 0.05).*
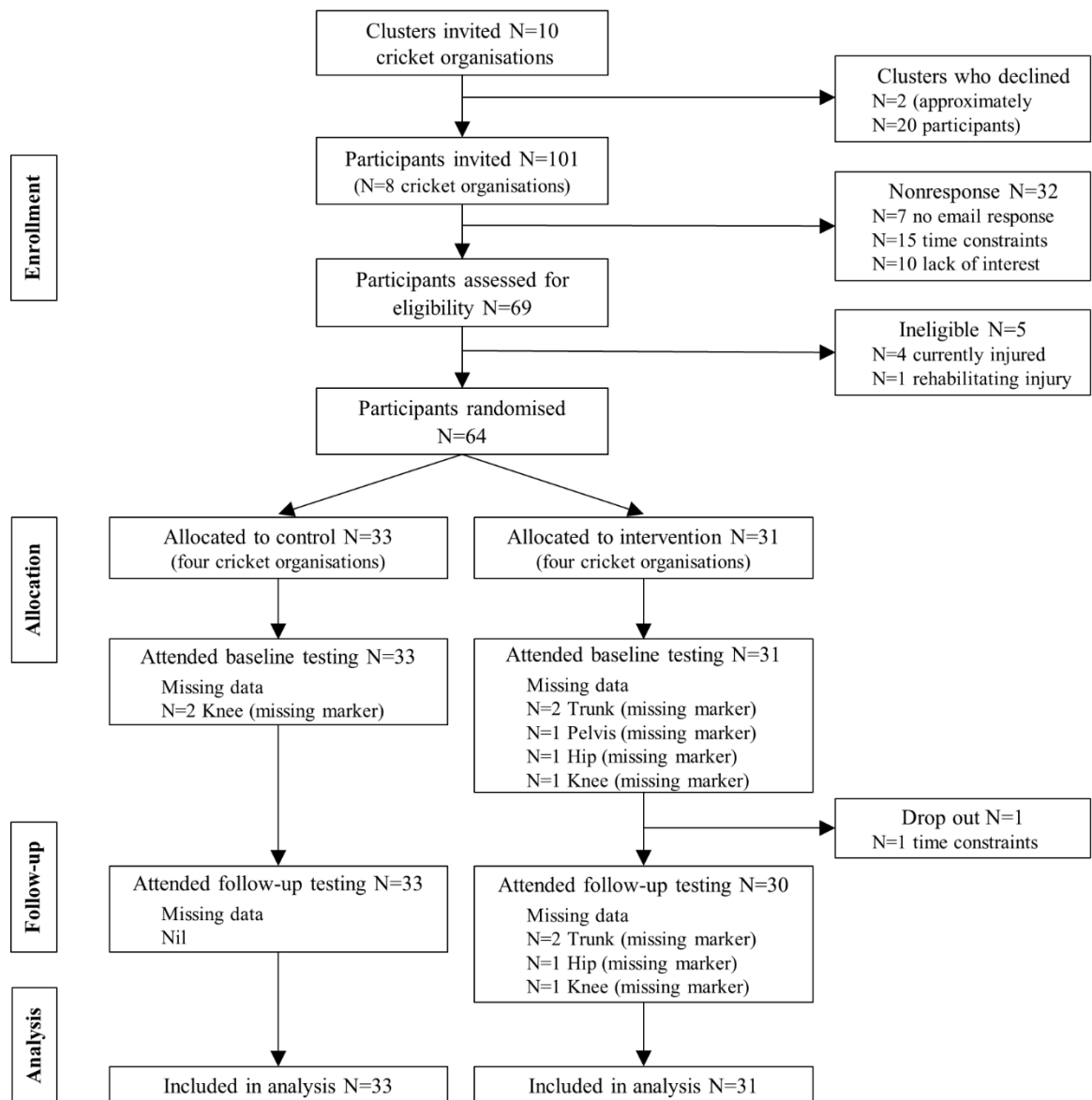
Figure 5.1 Flow of participants through Chapter 5.

Table 5.2 Outcome results and treatment effects Chapter 5.

Outcome	Intervention n=31	Control n=33	Treatment effect	Cohen's d	ICC
Shoulder counter-rotation					
Baseline	21.4 ± 9.5	25.7 ± 8.9			
Follow-up	20.4 ± 8.8	27.9 ± 10.9	-3.8 (-7.2 to -0.3)*	0.38	0.13
Lateral trunk flexion FFC					
Baseline	16.4 ± 9.0	16.6 ± 9.7			
Follow-up	16.7 ± 7.8	15.7 ± 8.7	1.2 (-2.5 to 4.8)	0.14	0.12
Lateral trunk flexion BR					
Baseline	45.9 ± 7.2	47.6 ± 7.7			
Follow-up	44.1 ± 5.2	46.0 ± 9.2	-0.5 (-3.0 to 2.0)	0.07	0.10
Relative lateral trunk flexion					
Baseline	34.8 ± 4.9	37.7 ± 5.7			
Follow-up	34.1 ± 3.5	38.3 ± 5.6	-2.2 (-4.0 to -0.5)*	0.49	0.10
Pelvis rotation FFC					
Baseline	233.5 ± 12.4	232.1 ± 13.1			
Follow-up	233.6 ± 10.1	233.5 ± 13.0	0.9 (-4.0 to 2.2)	0.08	0.05
Pelvis rotation BR					
Baseline	283.5 ± 11.4	283.7 ± 12.0			
Follow-up	280.8 ± 9.7	282.2 ± 11.6	-1.1 (-5.7 to 3.6)	0.10	0.15
Front hip angle FFC					
Baseline	45.4 ± 10.8	42.6 ± 7.8			
Follow-up	45.0 ± 8.5	41.2 ± 7.2	1.6 (-3.6 to 6.7)	0.20	0.13
Front hip angle BR					
Baseline	66.4 ± 12.9	62.3 ± 10.1			
Follow-up	65.2 ± 9.1	63.8 ± 11.8	-1.6 (-5.0 to 1.9)	0.15	0.23
Front knee angle FFC					
Baseline	14.9 ± 11.4	15.5 ± 10.4			
Follow-up	13.9 ± 10.5	15.4 ± 10.1	-1.1 (-4.5 to 2.3)	0.10	0.16
Front knee angle BR					
Baseline	40.4 ± 17.3	39.5 ± 20.5			
Follow-up	43.1 ± 16.7	40.8 ± 21.7	1.7 (-5.6 to 9.1)	0.09	0.09
Ball velocity (km·h⁻¹)					
Baseline	105.1 ± 8.5	102.5 ± 8.3			
Follow-up	105.4 ± 8.8	102.3 ± 8.1	1.1 (-7.5 to 9.7)	0.13	0.31

*All values in degrees (°) unless otherwise indicated, Baseline and follow-up outcome scores presented as mean (±) standard deviation, Treatment effect (95%CI) were adjusted for baseline score and cluster, ICC intra-cluster correlation coefficient at baseline, FFC front foot contact, BR ball release, * statistically significant $p<0.05$.*

Treatment effects (95% CI) indicate significant decreases favouring the intervention group for shoulder counter-rotation (-3.8°; -7.2° to -0.3°) and relative lateral trunk flexion (-2.2°; -4.0° to -0.5°) (Table 5.2). No between-group differences were observed for lateral trunk flexion at FFC (1.2°; -2. 5° to 4.8°), lateral trunk flexion at BR (-0.5°; -3.0° to 2.0°), pelvis rotation at FFC (0.9°; -4.0° to 2.2°), pelvis rotation at BR (-1.1°; -5.7° to 3.6°), front hip angle at FFC (1.6°; -3.6° to 6.7°), front hip angle at BR (-1.6°; -5.0° to 1.9°), front knee angle at FFC (-1.1°; -4.5° to 2.3°), front knee angle at BR (1.7°; -5.6° to 9.1°), or ball velocity (1.1 km·h^{-1}; -7.5 km·h^{-1} to 9.7 km·h^{-1}) (Table 5.2). When examining the shoulder counter-rotation in the intervention group, 7/28 players (24%) were above the recommended threshold (i.e., >30°) at baseline and 4/24 (14%) were above the threshold at follow-up. In the control group 10/33 players (30%) were at risk at baseline and 14/33 (42%) were at risk at follow-up. Mean shoulder counter-rotation in the control group also increased by 2.2° between testing sessions ($d = 0.22$).

5.5 Discussion

This study investigated the effect of an exercise-based IPP on bowling kinematics in a group of community-level adolescent pace bowlers. Performing the eight-week exercise-based IPP at training, in place of the usual warm-up, decreased shoulder counter-rotation and relative lateral trunk flexion. These findings may have implications for injury risk as shoulder counter-rotation and lateral trunk flexion have been previously linked to low back injuries in pace bowlers [31, 52, 62].

The reduction in the proportion of bowlers in the intervention group with excessive shoulder counter-rotation from baseline (24%) to follow up (14%) is likely beneficial. Conversely in the control group, there was an increase in the proportion of bowlers with excessive shoulder counter-rotation from baseline (30%) to follow up (42%). Lumbar kinetics

were not examined in this study, however, results from an investigation which employed a finite element analysis suggest that the 2° difference in relative lateral trunk flexion could reduce the forces acting on the lumbar spine while bowling [86]. The approximate 2° treatment effect for relative lateral trunk flexion, however, is relatively small and could be a result of measurement error. Additional research is therefore needed to determine if changes in shoulder counter-rotation and relative lateral trunk flexion attenuate injury risk.

The mechanism underlying the changes in shoulder counter-rotation and relative lateral trunk flexion may be related to the improvements in shoulder strength, lower-limb strength, dynamic control, and trunk extensor endurance which were reported in Chapter 4 [167]. It is difficult to identify which of these neuromuscular improvements had the greatest effect on changing kinematics, however, improvements in stability of the lower-limb and lumbopelvic region, may have played a role [170].

The approximate 4° treatment effect for shoulder counter-rotation, albeit significant, is considerably lower than the 20° change reported by Ranson et al.[81] who implemented a coaching intervention over a two-year period. The 4° difference is also substantially lower than the 14° decrease in shoulder counter-rotation reported by Elliott et al.[52] who prescribed a series of educational seminars over 3-4-years. While this may indicate that coaching interventions are a more suited to modifying shoulder counter-rotation, the current study was only conducted over eight-weeks, in comparison to the 2-4 year intervention periods in the technique modification studies.

The studies by Ranson et al.[81] and Elliott et al.[52] also included a higher proportion of bowlers with >30° shoulder counter-rotation at baseline, 93% and 80% respectively. In the current study, however, only 24% of the bowlers in the intervention group had >30° shoulder counter-rotation at baseline. The small magnitude of change for shoulder counter rotation in the current study may have occurred because most bowlers already had low levels of shoulder

counter-rotation and therefore had little room for improvement. Other studies which have changed risk factors for knee injury, support this suggestion, with 'high-risk' athletes typically showing the greatest response to intervention [175].

There was a small effect size ($d = 0.22$) for the control group's 2.2° increase in shoulder counter-rotation between baseline and follow-up testing sessions. This finding may be associated with those reported in Chapter 4 where hip adductor strength, reach distance on the star excursion balance test, and trunk extensor endurance also reduced in the control group [167]. It is possible that the changes in the neuromuscular measures could have driven the changes in bowling kinematics seen in the control group [31]. It is unclear why the neuromuscular measures and bowling technique declined in the control group. However, in previous work by Carr et al.[165], where measures of strength and power decreased in elite cricketers over the course of the season, the authors concluded that training loads in cricket were too low to appropriately condition the bowlers [165]. The same explanation could apply to community-level bowlers who may begin the cricket season with elevated levels of strength and power as a result of their participation in other sports during the cricket off-season. It is also possible that the neuromuscular measures and bowling kinematics declined in the control group because in-season bowling loads were too fatiguing. This may be the case in the current study as those in control group bowled more overs per week and perceived their training sessions to be more intense than the players in the intervention group. Further research to confirm if bowlers naturally decline over the course of a season would be beneficial, as would research aiming to uncover why these declines occur.

There were no treatment effects for the angles of global lateral trunk flexion, pelvis rotation, front hip angle, and front knee angle. This may have occurred because the exercise-program was not reinforced with coaching instruction to change bowling kinematics [170]. In other team sports, exercise interventions that were reinforced with visual and verbal feedback

were among the most beneficial for modifying potentially injurious knee kinematics [170]. Future research involving community-level pace bowlers should therefore investigate if exercise-based approaches combined with coach instruction can change bowling kinematics.

The non-significant findings for the angles of global lateral trunk flexion, pelvis rotation, front hip angle, front knee angle, and ball velocity could have also been related to the exercises included in the current program. While this program was designed to change neuromuscular factors and evidence demonstrates it can do this effectively [151, 167], program-refinement may be needed to alter bowling kinematics and ball velocity. For example, side-bridge exercises could be used to target the posterior trunk muscles on the side opposite the bowling arm as these muscles may play an important role in controlling the levels of lateral trunk flexion between FFC and BR [66]. Additional dynamic neuromuscular control exercises for the lower-limb may also help reduce lateral trunk flexion angles and promote changes in the kinematics of the pelvis, hip and knee [31, 170]. As for shoulder counter-rotation, exercises to strengthen the trunk rotator muscles may provide benefit. To target improvements in ball velocity, exercises which increase pectoral strength, latissimus dorsi strength, lower-limb power, and sprint performance may be needed. In previous studies involving junior pace bowlers and adult community-level pace bowlers for example, bench-throw performance, one repetition max pull-up strength, static jump performance, and 20m sprint time were among the best predictors of ball velocity [176, 177].

While this study provides important information regarding the efficacy of exercise-based programs to modify bowling kinematics, it does include some limitations. Firstly, the program was prescribed by an Accredited Exercise Physiologist not a community-level coach. The findings of this study may therefore not generalise to programs implemented by community-level coaches. Nevertheless, the program includes simple exercises and was designed to be used by a coach with no previous experience in exercise prescription. The

coaches of the bowlers in this study were also free to continue their standard coaching practices and this likely included the prescription of drills to correct bowling technique. While this may have influenced the results, it is likely that players in both groups received a similar level of coaching support throughout the study. There was also no quantification of fatigued state prior to each testing session. While players refrained from physical activity on the day of testing, their level of fatigue could have influenced their performance. It is also important to note that the outcome assessor was not blind to group allocation at follow-up or during data analysis. While this approach is not ideal, the objective measures used to assess bowling kinematics, are typically less prone to bias [178].

5.6 Conclusion

The eight-week exercise-based IPP decreased shoulder counter-rotation and relative lateral trunk flexion within our cohort of community-level adolescent pace bowlers. Additional research is needed to confirm if these changes reduce injury risk. Some bowling kinematics changed in the control group throughout the study. Continued exercise-based IPP in the pre-season and in-season is therefore important. There were no significant changes for the global measures of lateral trunk flexion or the kinematics of the pelvis, hip or knee. It would be beneficial if future studies investigated if exercise programs reinforced with coaching instruction could modify these kinematics.

CHAPTER 6

THESIS DISCUSSION

6.1 Thesis Overview

In line with the TRIPP framework [23], the aim of this thesis was to systematically review risk factors for injury in adolescent pace bowlers and then design an IPP for community-level adolescent pace bowlers. Following this, the thesis aimed to assess if this program could modify neuromuscular risk factors and alter bowling kinematics.

The primary results of Chapter 2 demonstrate that bowling workload, neuromuscular deficiencies, and bowling biomechanics are risk factors for non-contact injury in adolescent pace bowlers. In Chapter 3, five key target areas for injury prevention were identified and these included; shoulder strength, hamstring strength, hip adductor strength, dynamic neuromuscular control of the lumbo-pelvic region and lower-limb, and trunk extensor endurance. Factors to facilitate potential uptake of an IPP at the community-level equipment were also considered in Chapter 3, such as the inclusion of exercises which were simple, time-efficient, enjoyable to perform, and non-reliant on equipment. After identifying the five key prevention areas and the facilitators for implementation, a specific IPP for adolescent pace bowlers was developed. In Chapters 4 and 5, the newly-developed IPP showed significant treatment effects favouring the intervention group for; shoulder strength (90°/s), hamstring strength (60°/s), hip adductor strength, SEBT reach distance, back endurance, shoulder counter-rotation and relative lateral trunk flexion.

6.2 Discussion of Findings

The following section will provide commentary around the process of injury prevention in community-level adolescent pace bowlers. Findings will be discussed in the context of the TRIPP framework and in line with other published work in this area.

The systematic review (Chapter 2) was the first in the literature to identify risk factors for injury in adolescent pace bowlers. The identified factors were similar to those found by

Olivier et al. [41] among adult pace bowlers. Both reviews for example, identified studies which linked bowling load, shoulder counter-rotation, and poor balance/control of the lower-limb to injury. Numerous risk factors for low back injury were also identified in Chapter 2. Several factors were related to the bowling action and these therefore lack generalisability to other sports. The neuromuscular factors, such as inadequate lower-limb control and poor trunk muscle endurance, however, may have implications for other sports, such as gymnastics [179], volleyball [180], and tennis [181], where low back injuries are common.

After identifying the risk factors for injury in pace bowlers, an IPP that was suitable at the community-level was developed (Chapter 3). The exercises in this IPP were similar to those presented in FIFA 11+ and FootyFirst, however, the current IPP also included exercises to target the shoulder [84, 119]. Following the publication of Chapter 3, another IPP for cricketers was published by Soomro et al. [182]. Given the similarities in the target population, there were several overlapping features in both programs. Soomro et al. [182] for example, included resistance exercises for the posterior shoulder, the Nordic hamstring exercise, several balance/control drills for the lower-limb, and trunk extensor endurance exercises. A major difference between the programs was the inclusion of the single-leg squat exercise in the current IPP. This exercise has implications for correcting lower-limb mechanics [170] which have been linked to increased lateral flexion while bowling in adolescent bowlers [31].The inclusion of the single-leg squat exercise was therefore a vital component in the current IPP. Soomro et al. [182], however, did include more exercises to target the upper limbs, such as push-ups and rows. While the effectiveness of the program by Soomro et al. [182] has not been assessed, the inclusion of these additional upper-limb exercises could potentially provide beneficial outcomes for shoulder injury prevention [183]. The push-ups which strengthen the pectoral muscles could also aid in increasing ball speed, as bench throw performance (an assessment of pectoral muscle power) is one of the best predictors of ball speed in junior fast bowlers [176].

The results of Chapters 4 and 5 indicate that the IPP was able improve a number of neuromuscular factors and bowling kinematics. The FIFA 11+ also provides similar benefits, with studies investigating this program reporting improvements in muscle strength, muscle power, sprint speed and balance/proprioception [97, 184]. While injury risk was not investigated in this thesis, systematic reviews demonstrate that the FIFA 11+ can reduce the risk of injury by approximately 30-40% [184, 185]. It is therefore possible that with future research and continued refinement of the current IPP, similar results could be achieved in a cricket-context.

The findings in Chapters 4 and 5, which are situated in Stage 4 of the TRIPP framework, also provide vital information about the attitudes of cricket organisations/players towards injury prevention. The response rates among the cricket organisations/players indicate that these groups are willing to take engage with injury prevention. Of the ten invited cricket organisations, 80% agreed to participate in this research. Within these organisations approximately 70% of players were also willing to be involved. The low dropout rates (n=1) are also promising and suggest players will persist with exercise programs once they are implemented.

Although this thesis makes a number of significant contributions to the literature, it does contain some limitations. In Chapters 4 and 5 for example, the outcome assessor was not blinded to group allocation at follow-up. It is therefore possible that some bias was introduced here. Nevertheless, most outcomes in these chapters were assessed objectively and these measures are typically less susceptible to bias [178]. The participants in Chapters 4 and 5 were also aware of their group allocation at follow-up and this may have affected their performance during outcome assessment. Despite this, blinding of the participants was not appropriate for this research, as the players were either required to complete an exercise-based IPP or train as normal. Efforts were made to reflect the real-world context in Chapters 4 and 5, however, the information provided to participants during recruitment, the short intervention period (eight-

weeks), and the delivery of the program by an Accredited Exercise Physiologist may affected the external validity of the findings [23].

6.3 Future Research Directions

The IPP developed in this thesis modified several injury risk factors, however a number of the neuromuscular factors and bowling kinematics did not change. Future refinement of the IPP may therefore be needed to modify these factors. A Delphi study, which achieves expert consensus on the various exercises included within an IPP, would be an ideal progression after this thesis. An example of a successful Delphi study can be found in work by Donaldson et al. [186], where an IPP to prevent lower-limb injury in Australian Football was developed. In this study, expert medical staff, physiotherapists, and sport scientists from the Australian Football League collaborated to determine which exercises should be included in the IPP and how these exercises should be progressed. Replication of this study in a cricket-context with assistance from national and/or state coaching/medical staff would be beneficial and could ultimately improve the efficacy of the current IPP.

Following this, it would be useful to assess if the IPP reduces injury risk in pace bowlers. Cluster-randomised control trial designs would be best suited here. Ensuring definitions of injury align with the recent International Consensus Statement on Injury Surveillance in Cricket [45] would also be necessary. It is recommended that injuries be defined as 'player reported' and 'general time loss'. Player reported injuries (i.e., a condition which the player or their parent/teacher deem to represent an injury) are suited at the community-level where medical staff may not be available. General time loss injuries (i.e., an injury that causes a player to be unavailable for match-play, regardless of whether a match or training was scheduled) are also ideal at the community-level as they are unaffected by season scheduling and therefore provide a more accurate representation of injury-burden. Future studies should also control for

confounding variables such as bowling load, as this factor can influence injury risk [26, 29]. A bowler for example, may have appropriate bowling kinematics and adequate levels of strength, balance and endurance, yet still sustain an injury because their bowling load was inappropriate

As discussed in Chapter 5, it would be useful to reinforce exercise-based approaches with coach instruction aimed at changing bowling technique, as this approach appears to be useful in other studies aiming to change knee kinematics [164]. When designing the interventions to change bowling kinematics, researchers need to ensure they consider the context of implementation. This is especially important at the community-level, where an inexperienced coach may not have the expertise to identify poor kinematics and prescribe appropriate coaching drills for remediation.

If exercise-based IPPs are able attenuate injury risk in adolescent pace bowlers, it would be useful to turn our attention to Stage 5 of the TRIPP framework, which considers the various motivators and barriers to real-world program implementation [23]. An important step in this stage is to understand the attitudes towards injury in community-level cricket [23]. There is some pre-existing literature in this space from White et al. [187], who investigated the perceptions of injury risk in junior cricketers (Under 12s, 14s, and 16s). The study revealed that cricketers had relatively accurate perceptions of injury risk [187]. Injury risk associated with bowling was also higher among the Under 16s, indicating this group may be more receptive to partaking in exercise-based IPPs aimed at preventing bowling injuries [187, 188].

Future research should also consider the coaches' attitude toward IPPs because they are typically the one responsible for introducing and prescribing programs to their players [115, 189]. In other sports, coaches generally have favourable views towards IPPs but lack confidence to prescribe an intervention [115]. If this was also the case in cricket, it would be beneficial to provide coaches with additional education regarding program delivery. Coaches are also more likely to implement an IPP if it improves performance [190]. Examining if IPPs improve

bowling speed and accuracy is therefore recommended. Additional research situated in Stage 5 of the TRIPP framework should also aim to establish how constraints on time, facilities, finance, equipment and personal, influence program implementation; and how IPPs can be effectively marketed and promoted towards players, cricket clubs, and governing bodies [23].

Stage six of the TRIPP framework highlights the importance of examining program effectiveness in a real-world setting [23]. A recent controlled ecological study, which implemented an exercise program to prevent lower-limb injuries in Australian Football, provides a useful example of a study situated within Stage 6 of the TRIPP framework [191]. This study demonstrated that hospital-treated lower-limb injuries related to Australian Football could be reduced within a specific geographical region where an IPP was introduced. A key element to the success of this study was the level of support provided to the clubs performing the IPP [192]. Support included; small-scale marketing strategies to create awareness, the distribution of program manuals to clubs, coach education, and continued coach mentoring [192]. The ecological approach taken to prevent injury in Australian Football should be replicated in future investigations aiming to attenuate injury risk in community-level adolescent pace bowlers [191, 192].

6.4 Practical Applications

The practical recommendations based on the studies presented in this thesis are:

1. Neuromuscular deficiencies, inappropriate bowling workload, and poor bowling biomechanics are associated with injury in adolescent pace bowlers (Chapter 2). Practitioners could use this information to help identify pace bowlers at risk of injury.

2. Adolescent pace bowlers who are susceptible to non-contact injury and have associated neuromuscular risk factors will likely benefit for exercise-based programs (Chapter 3).

3. Cricket organisations are encouraged to implement exercise-based IPPs, as these programs can be effectively integrated into normal cricket training sessions at the community-level (Chapters 4 and 5).

4. Exercise-based IPPs can improve shoulder strength, hamstring strength, hip adductor strength, SEBT reach distance, back endurance, shoulder counter-rotation, and relative lateral trunk flexion in community-level adolescent pace bowlers (Chapters 4 and 5).

5. Coaches, players and parents should be aware that neuromuscular risk factors and bowling kinematics may worsen in pace bowlers who do not perform exercise-based injury prevention (Chapters 4 and 5).

6.5 Final Summary

Developing and implementing injury prevention strategies for community-level adolescent pace bowlers can provide many benefits. This thesis makes a significant contribution to the process of injury prevention in this population by; 1) providing the first systematic review to identify injury risk factors in adolescent pace bowlers; 2) developing a new exercise-based IPP appropriate for community-level cricketers; and 3) demonstrating that this exercise-based IPP can modify risk factors for injury. Ultimately it is hoped that the findings in this thesis provide the foundation for future research aimed at reducing injury risk within our community-level adolescent pace bowlers.

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Appendix A Systematic Review Syntax

Population: (cricket OR cricketer OR cricketers OR cricketing OR Bowler[title/abstract] OR bowlers[title/abstract] OR bowling[title/abstract])	

Injury terms and risk factors: AND ("Wounds and Injuries/anatomy and histology"[Mesh] OR "Wounds and injuries/epidemiology"[Mesh] OR "Wounds and Injuries/etiology"[Mesh] OR "Wounds and Injuries/injuries"[Mesh] OR "Wounds and Injuries/ physiology"[Mesh] OR "Wounds and Injuries/prevention and control"[Mesh] OR "Wounds and Injuries/radiography" [Mesh] OR "Wounds and Injuries/rehabilitation"[Mesh] OR "Wounds and Injuries/therapeutic use"[Mesh] OR "Wounds and Injuries/therapy"[Mesh] OR "Wounds and Injuries/ultrasonography"[Mesh] OR "Acute Pain/epidemiology"[Mesh] OR "Acute Pain/etiology"[Mesh] OR "Acute Pain/physiology"[Mesh] OR "Acute Pain/prevention and control"[Mesh] OR "Acute Pain/radiography"[Mesh] OR "Acute Pain/rehabilitation"[Mesh] OR "Acute Pain/therapy"[Mesh] OR "Acute Pain/ultrasonography"[Mesh] OR "Myalgia/anatomy and histology"[Mesh] OR "Myalgia/epidemiology"[Mesh] OR "Myalgia/etiology"[Mesh] OR "Myalgia/physiology"[Mesh] OR "Myalgia/ prevention and control"[Mesh] OR "Myalgia/radiography"[Mesh] OR "Myalgia/rehabilitation"[Mesh] OR "Myalgia/ therapy"[Mesh] OR "Myalgia/ ultrasonography"[Mesh] OR "Fractures, Stress/anatomy and histology"[Mesh] OR "Fractures, Stress/epidemiology" [Mesh] OR "Fractures, Stress/etiology"[Mesh] OR "Fractures, Stress/ physiology" [Mesh] OR "Fractures, Stress/ prevention and control"[Mesh] OR "Fractures, Stress/radiography"[Mesh] OR "Fractures, Stress/rehabilitation" [Mesh] OR "Fractures, Stress/therapy"[Mesh] OR "Fractures, Stress/ultrasonography" [Mesh] OR "Intervertebral Disc Degeneration/anatomy and histology"[Mesh] OR "Intervertebral Disc Degeneration/ epidemiology" [Mesh] OR "Intervertebral Disc Degeneration/etiology"[Mesh] OR "Intervertebral Disc Degeneration/ physiology" [Mesh] OR "Intervertebral Disc Degeneration/prevention and control"[Mesh] OR "Intervertebral Disc Degeneration/ radiography" [Mesh] OR "Intervertebral Disc Degeneration/rehabilitation"[Mesh] OR "Intervertebral Disc Degeneration/therapy" [Mesh] OR "Intervertebral Disc Degeneration/ultrasonography"[Mesh] OR "Sprains and Strains/anatomy and histology" [Mesh] OR "Sprains and Strains/epidemiology"[Mesh] OR "Sprains and Strains/ etiology"[Mesh] OR "Sprains and Strains/physiology"[Mesh] OR "Sprains and Strains/prevention and control"[Mesh] OR "Sprains and Strains/radiography" [Mesh] OR "Sprains and Strains/rehabilitation"[Mesh] OR "Sprains and Strains/ therapy"[Mesh] OR "Sprains and Strains/ultrasonography"[Mesh] OR "Rupture/anatomy and histology"[Mesh] OR "Rupture/epidemiology" [Mesh] OR "Rupture/etiology"[Mesh] OR "Rupture/physiology"[Mesh] OR "Rupture/ prevention and control"[Mesh] OR "Rupture/ radiography"[Mesh] OR "Rupture/rehabilitation"[Mesh] OR "Rupture/ therapy"[Mesh] OR "Rupture/ ultrasonography" [Mesh] OR "Fractures, Bone/anatomy and histology"[Mesh] OR "Fractures, Bone/epidemiology" [Mesh] OR "Fractures, Bone/etiology"[Mesh] OR "Fractures, Bone/ physiology"[Mesh] OR "Fractures, Bone/ prevention and control"[Mesh] OR "Fractures, Bone/radiography "[Mesh] OR "Fractures, Bone/rehabilitation" [Mesh] OR "Fractures, Bone/therapy"[Mesh] OR "Fractures, Bone/ultrasonography "[Mesh] OR "Hernia/anatomy and histology"[Mesh] OR "Hernia/epidemiology" [Mesh] OR "Hernia/etiology"[Mesh] OR "Hernia/ physiology"[Mesh] OR "Hernia/prevention and control"[Mesh] OR "Hernia/radiography"[Mesh] OR "Hernia/ rehabilitation"[Mesh] OR "Hernia/therapy"[Mesh] OR "Ultrasonography/ hernia"[Mesh] OR "Hernia/ ultrastructure "[Mesh] OR "Shoulder Impingement Syndrome/anatomy and histology"[Mesh] OR "Shoulder Impingement Syndrome/ epidemiology"[Mesh] OR "Shoulder Impingement Syndrome/etiology"[Mesh] OR "Shoulder Impingement Syndrome/ physiology"[Mesh] OR "Shoulder Impingement Syndrome/prevention and control"[Mesh] OR "Shoulder Impingement Syndrome/radiography" [Mesh] OR "Shoulder Impingement Syndrome/ rehabilitation"[Mesh] OR "Shoulder Impingement Syndrome/therapy" [Mesh] OR "Rotator Cuff/anatomy and histology" [Mesh] OR "Rotator Cuff/ etiology"[Mesh] OR "Rotator Cuff/growth and development" [Mesh] OR "Rotator Cuff/ injuries"[Mesh] OR "Rotator Cuff/physiology"[Mesh] OR "Rotator Cuff/ radiography"[Mesh] OR "Rotator Cuff/therapy" [Mesh] OR "Rotator Cuff/ ultrasonography"[Mesh] OR "Rotator Cuff/ ultrastructure"[Mesh] OR "Dislocations/ anatomy and histology"[Mesh] OR "Dislocations/epidemiology"[Mesh] OR "Dislocations/etiology"[Mesh] OR "Dislocations/ injuries"[Mesh] OR "Dislocations/physiology"[Mesh] OR "Dislocations/prevention and control"[Mesh] OR "Dislocations/ radiography" [Mesh] OR "Dislocations/ rehabilitation" [Mesh] OR "Dislocations/therapy"[Mesh] OR "Dislocations/ ultrasonography "[Mesh] OR "Spondylosis/anatomy and histology"[Mesh] OR "Spondylosis/epidemiology" [Mesh] OR "Spondylosis/ etiology"[Mesh] OR "Spondylosis/ physiology"[Mesh] OR "Spondylosis/ prevention and control"[Mesh] OR "Spondylosis/radiography"[Mesh] OR "Spondylosis/rehabilitation "[Mesh] OR "Spondylosis/therapy" [Mesh] OR "Spondylosis/ ultrasonography"[Mesh] OR "Spondylolysis/anatomy and histology" [Mesh] OR Spondylolysis/ epidemiology"[Mesh] OR "Spondylolysis/etiology" [Mesh] OR "Spondylolysis/ physiology" [Mesh] OR "Spondylolysis/ prevention and control"[Mesh] OR "Spondylolysis/radiography"[Mesh] OR "Spondylolysis/ rehabilitation"[Mesh] OR "Spondylolysis/therapy"[Mesh] OR "Spondylolysis/ultrasonography"[Mesh] OR "Spondylolisthesis/anatomy and histology"[Mesh] OR "Spondylolisthesis/ epidemiology"[Mesh] OR "Spondylolisthesis/ etiology"[Mesh] OR "Spondylolisthesis/physiology" [Mesh] OR "Spondylolisthesis/prevention and control"[Mesh] OR "Spondylolisthesis/ radiography"[Mesh] OR "Spondylolisthesis/ rehabilitation"[Mesh] OR "Spondylolisthesis/therapy" [Mesh] OR "Spondylolisthesis/ ultrasonography"[Mesh] OR injury OR injuries OR pain OR painful OR sore OR soreness OR damage OR trauma OR symptomatic OR abnormal OR abnormality OR abnormalities OR defect OR defects OR degeneration OR impairment OR strain OR strains OR sprain OR sprains OR tear OR tears OR rupture OR fracture OR fractures OR "stress fracture" OR "stress fractures" OR lesion OR lesions OR microtrauma OR micro damage OR "micro damage" OR herniation OR impingement OR dislocation OR spondylosis OR spondylolysis OR spondylolisthesis OR "Medical attention" OR "risk factor" OR "risk factors" OR biomechanics OR biomechanical OR kinematics OR kinematic OR kinetics OR kinetic OR technique OR force OR load OR "bowling action" OR "counter rotation" OR "Biomechanical Phenomena/ classification"[Mesh] OR "Biomechanical Phenomena/ education"[Mesh] OR "Biomechanical Phenomena/ etiology" [Mesh] OR "Biomechanical Phenomena/physiology" [Mesh] OR workload OR workloads OR overuse OR asymmetry OR asymmetrical OR asymmetries OR morphology OR morphologies OR "Cross sectional area")

Excluded: NOT (gryllus OR gryllidae OR gryllacrididae OR teleogryllus OR "case reports" [Publication Type])

Appendix B Modified Newcastle-Ottawa Quality Assessment (Cross-sectional)

Note: A study can be awarded a maximum of one star for each numbered item within the Selection and Outcome categories. A maximum of two stars can be given for Comparability

Selection

1) <u>Representativeness of the sample</u>
   a) truly representative of the average in the target population. (all subjects or random sampling) ✸
   b) somewhat representative of the average in the target population. (non-random sampling) ✸
   c) selected group of users.
   d) no description of the sampling strategy.

2) <u>Sample size</u>
   a) justified and satisfactory. ✸
   b) not justified.

3) <u>Non-respondents</u>
   a) comparability between respondents and non-respondents characteristics is established, and the response rate is satisfactory. ✸
   b) the response rate is unsatisfactory, or the comparability between respondents and non-respondents is unsatisfactory.
   c) no description of the response rate or the characteristics of the responders and the non-responders.

4) <u>Ascertainment of exposure</u>
   a) secure record (eg surgical records) ✸
   b) structured interview ✸
   c) written self-report
   d) no description

Comparability

1) <u>The subjects in different outcome groups are comparable, based on the study design or analysis. Confounding factors are controlled</u>
   a) the study controls for the most important factor (select one). ✸
   b) the study control for any additional factor. ✸

Outcome

1) <u>Assessment of outcome</u>
   a) independent blind assessment ✸
   b) record linkage ✸
   c) self-report
   d) no description

2) <u>Statistical test</u>
   a) the statistical test used to analyze the data is clearly described and appropriate, and the measurement of the association is presented, including confidence intervals and the probability level (p value). ✸
   b) the statistical test is not appropriate, not described or incomplete.

Appendix C Newcastle-Ottawa Quality Assessment (Cohort studies)

Note: A study can be awarded a maximum of one star for each numbered item within the Selection and Outcome categories. A maximum of two stars can be given for Comparability.

Selection

1) Representativeness of the exposed cohort
   a) truly representative of the average _____ (describe) in the community ✳
   b) somewhat representative of the average _____ in the community ✳
   c) selected group of users eg nurses, volunteers
   d) no description of the derivation of the cohort

2) Selection of the non-exposed cohort
   a) drawn from the same community as the exposed cohort ✳
   b) drawn from a different source
   c) no description of the derivation of the non-exposed cohort

3) Ascertainment of exposure
   a) secure record (eg surgical records) ✳
   b) structured interview ✳
   c) written self-report
   d) no description

4) Demonstration that outcome of interest was not present at start of study
   a) yes ✳
   b) no

Comparability

1) Comparability of cohorts on the basis of the design or analysis
   a) study controls for _____ (select the most important factor) ✳
   b) study controls for any additional factor ✳ (This criteria could be modified to indicate specific control for a second important factor.)

Outcome

1) Assessment of outcome
   a) independent blind assessment ✳
   b) record linkage ✳
   c) self-report
   d) no description

2) Was follow-up long enough for outcomes to occur
   a) yes (select an adequate follow-up period for outcome of interest) ✳
   b) no

3) Adequacy of follow-up of cohorts
   a) complete follow-up - all subjects accounted for ✳
   b) subjects lost to follow-up unlikely to introduce bias - small number lost - > ____ % (select an adequate %) follow-up, or description provided of those lost) ✳
   c) follow-up rate < ____% (select an adequate %) and no description of those lost
   d) no statement

Appendix D Exercise Program Manual

The following exercise program was developed in accordance with the TRIPP framework, previous research into cricket injuries/risk factors, and established principles for exercise program development/prescription. The team of Exercise Scientists and Physiologist behind the development of this program have extensive expertise in the area of exercise program design and prescription.

Exercise-based injury prevention for adolescent cricketers

MRL Forrest, BR Scott, JJ Hebert, AR Dempsey

Contents

This program has been designed to reduce injury risk in adolescent cricketers and can be used as a stand-alone program or as a warm-up before a training session or match. Players are recommended to perform two sessions of the program per week and can use it in the preseason and the season. Each session starts with a dynamic warm-up and is followed by a series of exercises to improve muscle strength (shoulder muscles, groin muscles and hamstrings), increase dynamic neuromuscular control (movement control/stability of the low back, pelvis and legs) and improve endurance of the back muscles.

Three progressive stages are included in the program: a basic phase incorporating simple exercises which are ideal for teaching correct exercise technique (stage 1); an intermediate stage where players continue to build a base of strength, dynamic neuromuscular control and endurance (stage 2); and an advanced phase which incorporates exercises that are more dynamic and sport-specific (stage 3). Players should not perform an exercise if it causes them pain and injured athletes or those with a serious health condition should seek medical approval before participating in the program. If an athlete experiences pain during a stage 2 or stage 3 exercise, it is appropriate to return to the previous stage.

Players should progress through the stages on an individual basis when they can complete the prescribed volume with correct technique. For ease of use, however, coaches can progress all players through the program at the same time. To assist coaches in making decisions about progressing, a guide has been placed after each exercise (see below for an example of the progression guide) and pictures of correct exercise technique have been provided.

When to progress to the next stage?

The green arrow indicates the ideal method for progressing.

The orange arrow indicates an acceptable but less-optimal method.

Perform this warm-up before each session. Once this has been completed you can begin exercises to improve muscle strength, dynamic neuromuscular control and muscle endurance.

Field set-up

20 metres
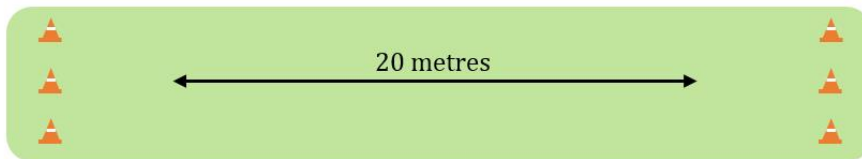
Jog + arm circles

Jog for 20m while continually swinging the arms in circles.

Heel flicks

Run for 20m while bringing the heels to the buttocks.

High knees

Run for 20m while lifting the thighs high.

Side steps

Side step between the cones for a total of 40m. Stay facing the same way throughout.

Shuttle runs

Run at 50% speed, 75% and then 100% (run 20m for each speed).

Shoulder strengthening (resistance band shoulder rotation)

Description: With your shoulder turned out, your elbow by your side and flexed to 90° (position 1), internally rotate the shoulder (position 2) and then return to the start position. This movement should take 4 seconds (3 seconds in and 1 second out).

Volume: 2x10 repetitions per arm.

Correct technique:
- ✓ Achieve full external/internal range of motion (range may vary between players).
- ✓ Upper arm locked to the side of the body throughout the exercise.
- ✓ Resistance band anchored to the side and under tension throughout the exercise.
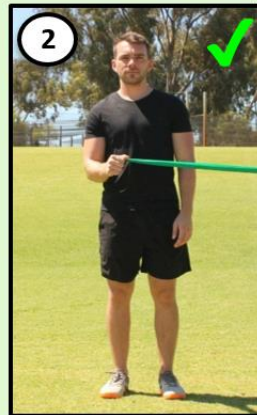
Incorrect technique:
- ✗ Moving the upper arm away from the body.
- ✗ Rotating the trunk.
- ✗ Poor scapular stability (shrugging the shoulders or rounding the shoulders forward).

When to progress to the next stage?

➡ If you can complete the prescribed volume with correct technique and have performed at least 2 weeks (4 sessions).

➡ After completing 2 weeks (4 sessions).

Shoulder strengthening (cricket bat shoulder rotation)

If you don't have access to a resistance band, perform this exercise instead

Description: With your shoulder turned out, your elbow by your side and flexed to 90° (position 1), internally rotate the shoulder (position 2) and then return to the start position. This movement should take 4 seconds (3 seconds down and 1 second up).

Volume: 10 repetitions per arm.

Correct technique:
- ✓ Achieve full external/internal range of motion (range may vary between players).
- ✓ Upper arm locked to the side of the body throughout the exercise.
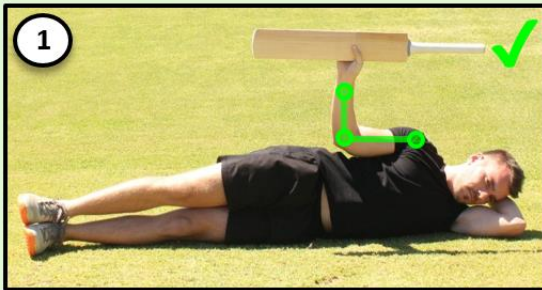
Incorrect technique:
- ✗ Tilting or rotating the trunk backwards.
- ✗ Bending the wrist.
- ✗ Poor scapular stability (shrugging the shoulders or rounding the shoulders forward).

When to progress to the next stage?

➡ If you can complete the prescribed volume with correct technique and have performed at least 2 weeks (4 sessions).

➡ After completing 2 weeks (4 sessions).

Groin strengthening (side-lying hip adduction)

Description: Lie on your side with your top leg bent and foot on the ground (position 1). Then lift your bottom leg up to reach position 2 and then return to position 1. This movement should take 3 seconds (1 second up and 2 seconds down).

Volume: 10 repetitions per leg.

Correct technique:
- ✓ Achieve full range of motion when lifting the leg (range may vary between players).
- ✓ Keep the bottom leg straight when lifting.
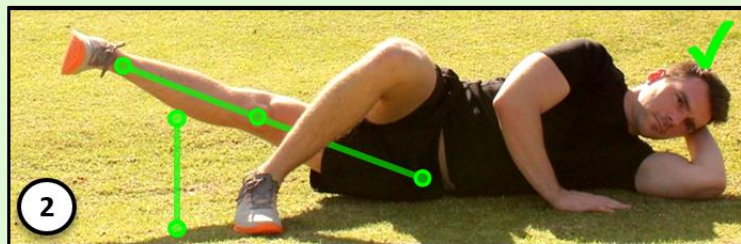
Incorrect technique:
- ✗ Bending at the hips.
- ✗ Tilting or rotating the body.

When to progress to the next stage?

➡ If you can complete the prescribed volume with correct technique and have performed at least 2 weeks (4 sessions).

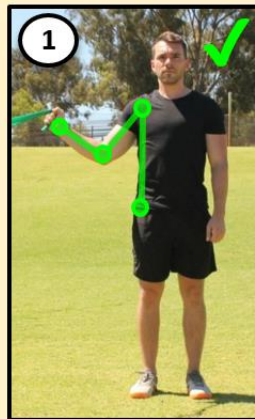➡ After completing 2 weeks (4 sessions).

Hamstring strengthening (Nordic hamstring exercise)

Description: Slowly fall forwards (position 1). When you can no longer resist the fall, put your hands out (position 2) and push yourself back to the start position. Refer to page 27 for information regarding correct partner technique.

Volume: 3-5 repetitions (3 repetitions in the beginning then increase by one repetition per session until you can perform 5). Choose a partner who is about your size.
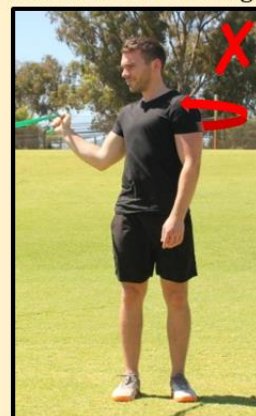
Correct technique:
- ✔ Knees, hips shoulders and head should align.
- ✔ Resist the fall for as long as possible (approximately 3 seconds).

Incorrect technique:
- ✘ Bending at the hips.
- ✘ Arching the back.

If you are having difficulty resisting the fall for approximately 3 seconds, aim to gradually build-up to this throughout this stage (i.e., session 1 resist for 1.5 seconds, session 2 resist for 2 seconds, session 3 resist for 2.5 seconds).

When to progress to the next stage?

➡ If you can complete the prescribed volume with correct technique and have performed at least 2 weeks (4 sessions).

➡ After completing 2 weeks (4 sessions).

Dynamic neuromuscular control (single-leg ball throws)

Description: Stand on one leg and throw/catch a ball with your partner. Throw the ball to various locations (i.e. above the head/below the knees and out to the side of the body).

Volume: 1 minute on the left leg and 1 minute on the right leg (approximately 20 catches per partner per leg).

Correct technique:
- ✔ Slightly bend the knee of the stance leg.
- ✔ Keep your balance and don't shuffle the stance foot.
- ✔ Throws are challenging but still catchable (i.e., should not cause a loss of balance).

Incorrect technique:
- ✗ Knee collapsing inwards and toe pointing outwards.
- ✗ Excessive movements of the pelvis and trunk.

When to progress to the next stage?

➡ If you can complete the prescribed volume with correct technique and have performed at least 2 weeks (4 sessions).

➡ After completing 2 weeks (4 sessions).

Dynamic neuromuscular control (squats)

Description: From position 1, bend at the knees and hips to reach position 2. Players can also perform a full-depth squat (position 3) if mobility and technical proficiencies allow.

Volume: 10 repetitions.

Correct technique:
- ✔ Straight back, flex knees to at least 90° and knees behind the toes.
- ✔ Knees and toes should align when looking from the front.

Incorrect technique:
- ✗ Knee collapsing inwards and toe pointing outwards.
- ✗ Trunk leaning too far forward.
- ✗ Rounding the back.

When to progress to the next stage?

→ If you can complete the prescribed volume with correct technique and have performed at least 2 weeks (4 sessions).

→ After completing 2 weeks (4 sessions).

Dynamic neuromuscular control (lunges)

Description: From position 1, bend at the knees and hips to reach position 2.

Volume: 5 repetitions per leg (alternate the front leg between repetitions).

Correct technique:
- ✔ Straight back, flex the knee to 90° and knee behind the toe.
- ✔ Knee and toe should align when looking from the front.
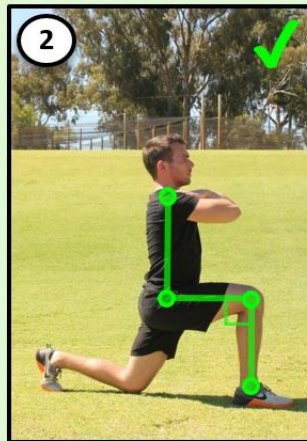
Incorrect technique:
- ✘ Knee collapsing inwards and toe pointing outwards.
- ✘ Trunk leaning too far forward.
- ✘ Excessive movements of the pelvis and trunk.

When to progress to the next stage?

➡ If you can complete the prescribed volume with correct technique and have performed at least 2 weeks (4 sessions).

➡ After completing 2 weeks (4 sessions).

Trunk extensor endurance (prone hold)

Description: With your feet, elbows and forearms on the ground (position 1), hold your body up for the required time.

Volume: 20–30 seconds (20 seconds in the beginning and then increase by 5 seconds per session until you can hold for 30 seconds).

Correct technique:

✓ Ankles, knees, hips, shoulders, and head aligned. Elbows directly below shoulders.
✓ Body lifted off the ground and remaining relatively still throughout the hold.
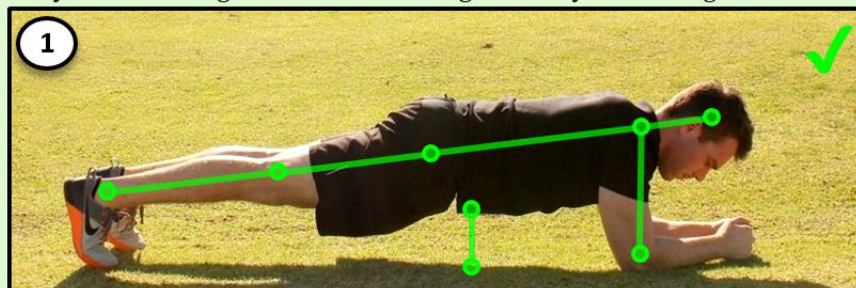
Incorrect technique:

✗ Arching up at the hips and flexing the neck forward.
✗ Body too low and arching the back.
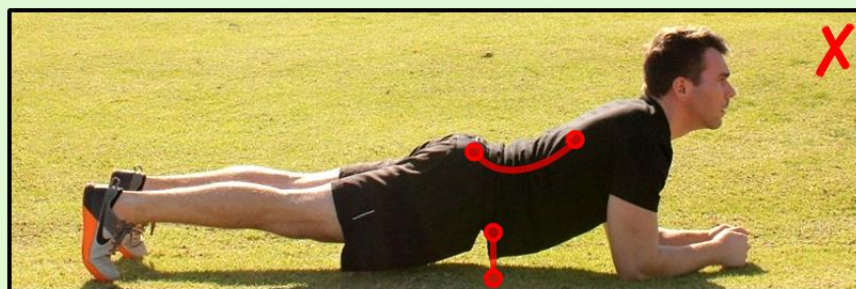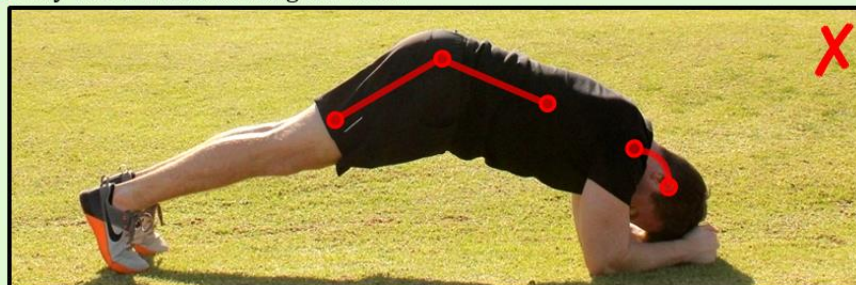
When to progress to the next stage?

➡ If you can complete the prescribed volume with correct technique and have performed at least 2 weeks (4 sessions).

➡ After completing 2 weeks (4 sessions).

Shoulder strengthening (resistance band external rotation 45°)

Description: With your shoulder turned out, upper arm 45° from your side and elbow flexed to 90° (position 1), internally rotate the shoulder (position 2) and then return to the start position. This movement should take 4 seconds (3 seconds in and 1 second out).

Volume: 2x10-15 repetitions per arm (10 repetitions in the beginning then increase by one repetition per session until you can perform 15).

Correct technique:
- ✓ Achieve full external range of motion (range may vary between players).
- ✓ Resistance band anchored in front and under tension throughout the exercise.

Incorrect technique:
- ✗ Moving the upper arm forwards.
- ✗ Rotating the trunk.
- ✗ Poor scapular stability (shrugging the shoulders or rounding the shoulders forward).

When to progress to the next stage?

➡ If you can complete the prescribed volume with correct technique and have performed at least 3 weeks (6 sessions).

➡ After completing 3 weeks (6 sessions).

Shoulder strengthening (cricket bat shoulder rotation 45°)

If you don't have access to a resistance band, perform this exercise instead

Description: With your shoulder turned out, upper arm 45° from your side and elbow flexed to 90 (position 1), internally rotate the shoulder (position 2) and then return to the start position. This movement should take 4 seconds (3 seconds down and 1 second up).

Volume: 10-15 repetitions per arm (10 repetitions in the beginning then increase by one repetition per session until you can perform 15).

Correct technique:
- ✓ Achieve full external/internal range of motion (range may vary between players).
- ✓ Ensure the upper arm remains still while rotating.

Incorrect technique:
- ✗ Tilting or rotating the trunk backwards.
- ✗ Bending the wrist.
- ✗ Poor scapular stability (shrugging the shoulders or rounding the shoulders forward).

When to progress to the next stage?

➡ If you can complete the prescribed volume with correct technique and have performed at least 3 weeks (6 sessions).

➡ After completing 3 weeks (6 sessions).

Groin strengthening (modified Copenhagen adduction exercise)

Description: From position 1, bring the feet together to reach position 2 (approximately 1 second). From there, slowly lower the leg back to position 1 (approximately 3 seconds). Refer to page 26 for information regarding correct partner technique.

Volume: 4-6 repetitions per leg (4 repetitions in the beginning then increase by one repetition per session until you can perform 6). Choose a partner who is about your size.

Correct technique:
- ✓ Open legs to approximately 50% of max range (range may vary between players).
- ✓ Completely lift the hips off the ground and align the ankle, knee, hip and shoulder.
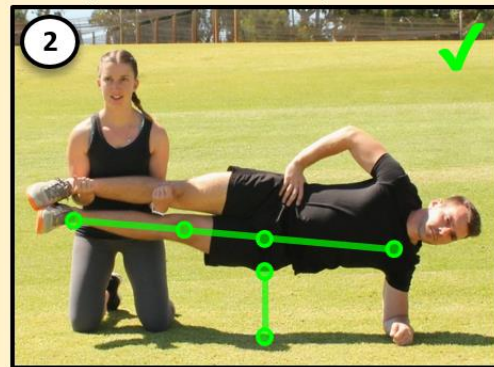
Incorrect technique:
- ✗ Using the arms to assist in lifting/lowering the body.
- ✗ Body not straight.

If you are having difficulty with this exercise you could aim to gradually build-up to the 3 second lower (i.e., session 1 lower for 1.5 seconds, session 2 lower for 2 seconds, session 3 lower for 2.5 seconds).

When to progress to the next stage?

→ If you can complete the prescribed volume with correct technique and have performed at least 3 weeks (6 sessions).

→ After completing 3 weeks (6 sessions).

Hamstring strengthening (Nordic hamstring exercise)

Description: Slowly fall forwards (position 1). When you can no longer resist the fall, put your hands out (position 2) and push yourself back to the start position. Refer to page 27 for information regarding correct partner technique.

Volume: 6-10 repetitions (6 repetitions in the beginning then increase by one repetition per session until you can perform 10). Choose a partner who is about your size.

Correct technique:
- ✓ Knee, hips shoulders and head should align.
- ✓ Resist the fall for as long as possible (approximately 3 seconds).

Incorrect technique:
- ✗ Bending at the hips.
- ✗ Arching the back.

When to progress to the next stage?

➡ If you can complete the prescribed volume with correct technique and have performed at least 3 weeks (6 sessions).
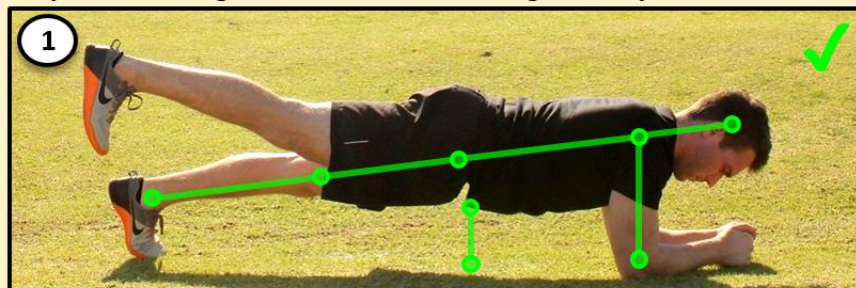
➡ After completing 3 weeks (6 sessions).

Dynamic neuromuscular control (opposite hand to toe)

Description: From position 1, slowly bend at the hips to reach position 2 (approximately 3 seconds) and then slowly return to position 1 (approximately 3 seconds). The hand on the opposite side should touch the toe (i.e., right hand to left toe).

Volume: 10-15 repetitions per leg (10 repetitions in the beginning then increase by one repetition per session until you can perform 15).

Correct technique:
- ✓ Keep your balance and don't shuffle the stance foot.
- ✓ Knee and toe should align when looking from the front.
- ✓ Keep your pelvis level.
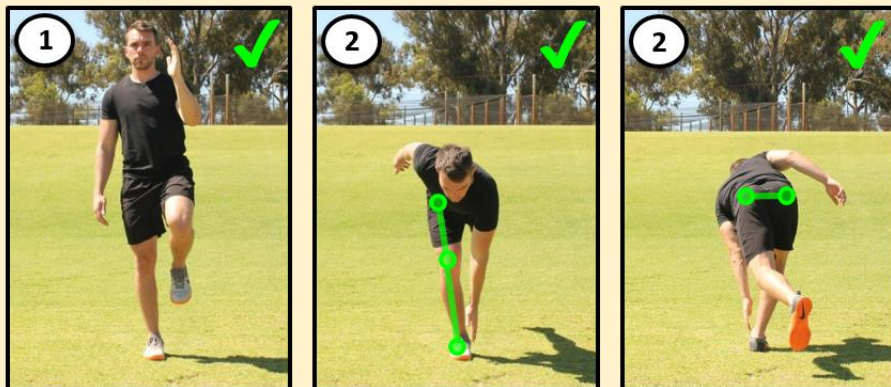
Incorrect technique:
- ✗ Knee collapsing inwards and toe pointing outwards.
- ✗ Excessive movements of the pelvis and trunk.

When to progress to the next stage?

➡ If you can complete the prescribed volume with correct technique and have performed at least 3 weeks (6 sessions).

➡ After completing 3 weeks (6 sessions).

Dynamic neuromuscular control (partner-assisted single-leg squats)

Description: From position 1, bend at the knees and hips to reach position 2.

Volume: 10-15 repetitions per leg (10 repetitions in the beginning then increase by one repetition per session until you can perform 15). Choose a partner who is about your size.

Correct technique:
- ✓ Keep your balance and don't shuffle the stance foot.
- ✓ Straight back, flex the knee to 90° and knee behind the toe.
- ✓ Knee and toe should align when looking from the front.

Incorrect technique:
- ✗ Knee collapsing inwards and toe pointing outwards.
- ✗ Trunk leaning too far forward.
- ✗ Excessive movements of the pelvis and trunk.

When to progress to the next stage?

→ If you can complete the prescribed volume with correct technique and have performed at least 3 weeks (6 sessions).

→ After completing 3 weeks (6 sessions).
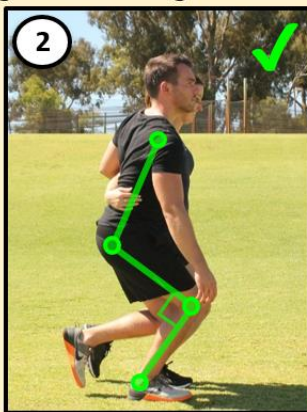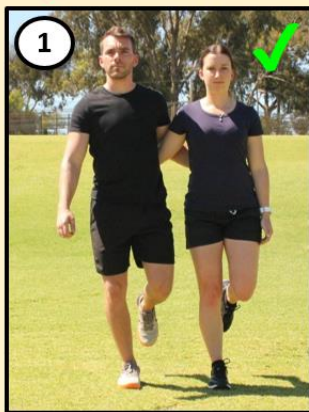
Dynamic neuromuscular control (double-leg jumps)

Description: Jump forward (picture 1), to the left (picture 2) and to the right (picture 3). Jump about 80% of your maximal distance.

Volume: 8-12 repetitions per direction (8 repetitions in the beginning then increase by one repetition per session until you can perform 12).

Correct technique:
✓Keep your balance and hold the landing for 2 seconds before jumping again.
✓Straight back, knees slightly bent and knees behind the toes (on landing).
✓Knee and toe should align when looking from the front.
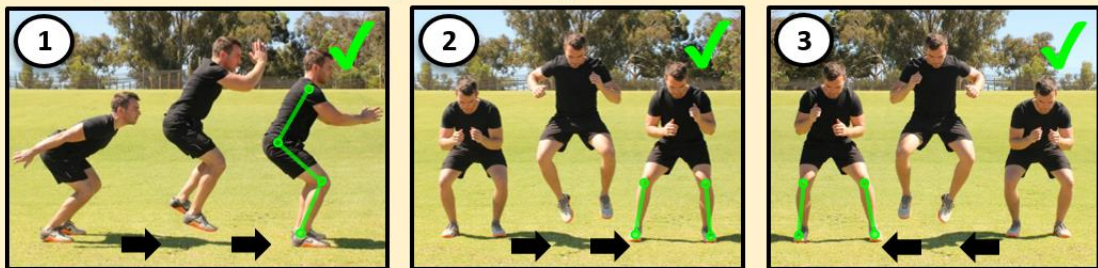
Incorrect technique:
✗Knee collapsing inwards and toe pointing outwards.
✗Trunk leaning too far forward.
✗Excessive movements of the pelvis and trunk.

When to progress to the next stage?

➡ If you can complete the prescribed volume with correct technique and have performed at least 3 weeks (6 sessions).

➡ After completing 3 weeks (6 sessions).

Trunk extensor endurance (prone hold with leg lift)

Description: Lift and hold the right leg off the ground for 2 seconds (position 1) and then place it back on the ground. Repeat this movement with the left leg (lifting the right leg then the left leg is considered one cycle).

Volume: 4-6 cycles (4 cycles in the beginning and then increase by 1 cycle per session until you can perform 6).

Correct technique:
✓ Ankle, knee, hips, shoulders, and head aligned. Elbows directly below shoulders.
✓ Body lifted off the ground and trunk remaining relatively still.

Incorrect technique:
✗ Arching up at the hips and flexing the neck forward.
✗ Body too low and arching the back.
✗ Excessive movement of the pelvis and trunk.

When to progress to the next stage?

➡ If you can complete the prescribed volume with correct technique and have performed at least 3 weeks (6 sessions).

➡ After completing 3 weeks (6 sessions).

Shoulder strengthening (resistance band external rotation 90°)

Description: With your shoulder turned out, upper arm 90° from your side and elbow flexed to 90 (position 1), internally rotate the shoulder (position 2) and then return to the start position. This movement should take 4 seconds (3 seconds down and 1 second up).

Volume: 2x10-15 repetitions per arm (10 repetitions in the beginning then increase by one repetition per session until you can perform 15).

Correct technique:
- ✓ Achieve full external range of motion (range may vary between players).
- ✓ Resistance band anchored in front and under tension throughout the exercise.

Incorrect technique:
- ✗ Moving the upper arm forwards.
- ✗ Rotating the trunk.
- ✗ Poor scapular stability (shrugging the shoulders or rounding the shoulders forward).

What should I do next?

If you can complete the maximally prescribed volume with correct technique for this stage, you should aim to maintain this throughout the season. You could make this exercise more challenging if you step further away from the anchor point or increase the thickness of the resistance band.

Shoulder strengthening (cricket bat shoulder rotation 90°)

If you don't have access to a resistance band, perform this exercise instead

Description: With your shoulder turned out, upper arm 90° from your side and elbow flexed to 90 (position 1), internally rotate the shoulder (position 2) and then return to the start position. This movement should take 4 seconds (3 seconds down and 1 second up).

Volume: 10-15 repetitions per arm (10 repetitions in the beginning then increase by one repetition per session until you can perform 15).

Correct technique:
- ✓ Achieve full external/internal range of motion (range may vary between players).
- ✓ Ensure the upper arm remains still while rotating.

Incorrect technique:
- ✗ Tilting or rotating the trunk backwards.
- ✗ Bending the wrist.
- ✗ Poor scapular stability (shrugging the shoulders or rounding the shoulders forward).

What should I do next?

If you can complete the maximally prescribed volume with correct technique for this stage, you should aim to maintain this throughout the season. You could make this exercise more challenging by holding the cricket bat further from its mid-point (i.e., holding near the splice or holding the handle).

Groin strengthening (Copenhagen adduction exercise)

Description: From position 1, bring the feet together to reach position 2 (approximately 1 second). From there, slowly lower the leg back to position 1 (approximately 3 seconds). Refer to page 26 for information regarding correct partner technique.

Volume: 8-12 repetitions each leg (8 repetitions in the beginning then increase by one repetition per session until you can perform 12). Choose a partner who is about your size.

Correct technique:

✓ Open legs to approximately 80% of max range (range may vary between players).
✓ Completely lift the hips off the ground and align the ankle, knee, hip and shoulder.
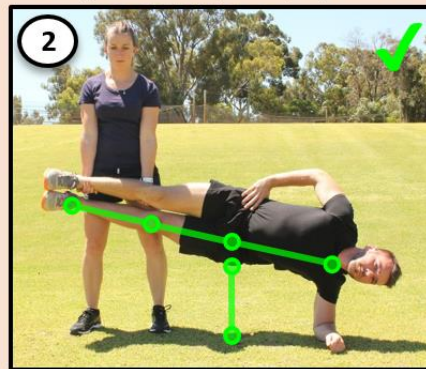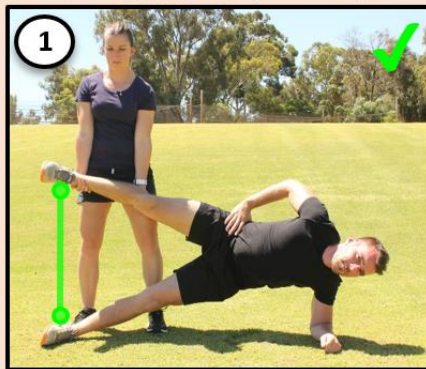
Incorrect technique:

✗ Using the arms to assist in lifting/lowering the body.
✗ Body not straight.

What should I do next?

If you can complete the maximally prescribed volume with correct technique for this stage, you should aim to maintain this throughout the season. You could make this exercise more challenging by increasing the time you take during the lowering phase.

Hamstring strengthening (Nordic hamstring exercise)

Description: Slowly fall forwards (position 1). When you can no longer resist the fall, put your hands out (position 2) and push yourself back to the start position. Refer to page 27 for information regarding correct partner technique.

Volume: 12-15 repetitions (12 repetitions in the beginning and then increase by one repetition per session until you can perform 15). Choose a partner who is about your size.

Correct technique:
- ✓Knee, hips shoulders and head should align.
- ✓Resist the fall for as long as possible (approximately 3 seconds).

Incorrect technique:
- ✗Bending at the hips.
- ✗Arching the back.

What should I do next?

If you can complete the maximally prescribed volume with correct technique for this stage, you should aim to maintain this throughout the season. You could make this exercise more challenging by holding a weight to your chest or by increasing the time of the lowering phase. Especially focus on holding the body in the positions closer to the ground for longer periods.

Dynamic neuromuscular control (single-leg squats)

Description: From position 1, bend at the knees and hips to reach position 2.

Volume: 8-12 repetitions per leg (8 repetitions in the beginning then increase by one repetition per session until you can perform 12).
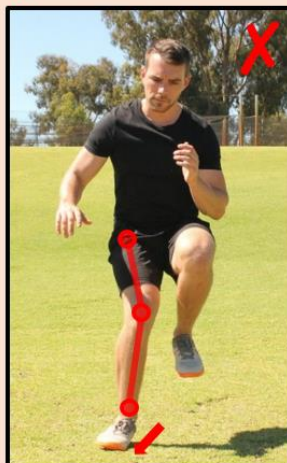
Correct technique:
- ✓ Keep your balance and don't shuffle the stance foot.
- ✓ Straight back, flex the knee to 90° and knee behind the toe.
- ✓ Knee and toe should align when looking from the front.

Incorrect technique:
- ✗ Knee collapsing inwards and toe pointing outwards.
- ✗ Trunk leaning too far forward.
- ✗ Excessive movements of the pelvis and trunk.

What should I do next?

If you can complete the maximally prescribed volume with correct technique for this stage, you should aim to maintain this throughout the season. You could make this exercise more challenging by squatting deeper (i.e., more than 90 °of knee flexion on the stance leg at position 2). It is vitally important to maintain correct technique when attempting this.

Dynamic neuromuscular control (single-leg jumps)

Description: While on one leg, jump forward (picture 1), to the left (picture 2) and to the right (picture 3). Jump about 80% of your maximal distance and land on one leg.

Volume: 6-8 repetitions per direction, per leg (6 repetitions in the beginning then increase by one repetition per session until you can perform 8).

Correct technique:
- ✓ Keep your balance and hold the landing for 2 seconds before jumping again.
- ✓ Straight back, knee slightly bent and knee behind the toe (on landing).
- ✓ Knee and toe should align when looking from the front.

Incorrect technique:
- ✗ Knee collapsing inwards and toe pointing outwards.
- ✗ Trunk leaning too far forward.
- ✗ Excessive movements of the pelvis and trunk.

What should I do next?

If you can complete the maximally prescribed volume with correct technique for this stage, you should aim to maintain this throughout the season. You could make this exercise more challenging by reducing the time on the ground between jumps (i.e., use your landing to explosively spring into the next jump). It is vitally important to maintain correct technique when attempting this.

Trunk extensor endurance (prone hold with leg + opposite arm lift)

Description: Lift and hold the right leg and left arm off the ground for 2 seconds (position 1) and then place them back on the ground. Repeat this movement with the left leg and right arm (lifting the right leg/left arm then the left leg/right arm is considered one cycle).

Volume: 4-6 cycles (4 cycles in the beginning and then increase by 1 cycle per session until you can perform 6).

Correct technique:
- ✓ Ankle, knee, hips, shoulders, and head aligned. Elbows directly below shoulders.
- ✓ Body lifted off the ground and trunk remaining relatively still.
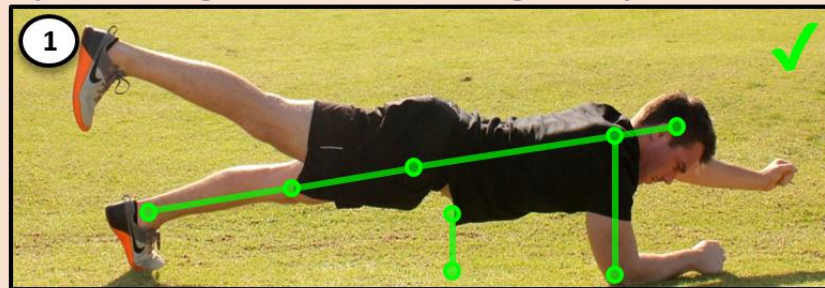
Incorrect technique:
- ✗ Arching up at the hips and flexing the neck forward.
- ✗ Body too low and arching the back.
- ✗ Excessive movement of the pelvis and trunk.

What should I do next?

If you can complete the prescribed volume with correct technique for this stage, you should aim to maintain this throughout the season. You could make this exercise more challenging by holding a cricket ball or a water bottle in the hand of the extended arm.

If you are acting as the partner during the Copenhagen adduction exercise, it is important to have correct technique. This will help protect you from potential injury and will also allow your partner to perform the exercise properly.

Modified Copenhagen adduction exercise

Correct partner technique:
- ✓ The person performing the exercise and the partner have similar body sizes.
- ✓ Firmly hold your partner's ankle and knee so the leg does not drop down during the exercise. Your partner could also rest their leg on a fence, step or box.
- ✓ While kneeling keep your body straight and low back neutral.

Copenhagen adduction exercise

Correct partner technique:
- ✓ The person performing the exercise and the partner have similar body sizes.
- ✓ Firmly hold your partner's ankle and knee so the leg does not drop down during the exercise. Your partner could also rest their leg on a fence, step or box.
- ✓ Slightly bend your knees, body straight and low back neutral.
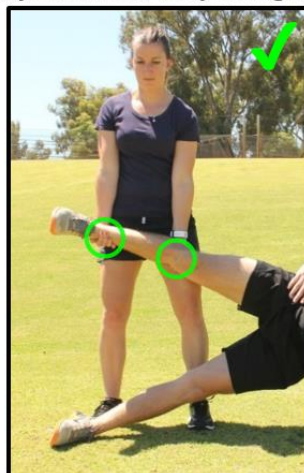
If you are acting as the partner during the Nordic hamstring exercise, it is important to have correct technique. This will help protect you from potential injury and will also allow your partner to perform the exercise properly.

Nordic hamstring exercise

Correct partner technique:

✓ The person performing the exercise and the partner have similar body sizes.

✓ Hips, back, shoulders and head aligned.

✓ Firmly hold your partner's ankles so their legs do not lift off the ground (use your body weight to help you push straight down).

Appendix E Modified Trunk Extensor Endurance Exercises in Chapters 4 and 5

Stage 1

Trunk extensor endurance (chest up)

Description: Place the arms by the side of the body and lift the chest and head approximately 5cm off the ground. Hold the position for 10 seconds.

**Volume:** 10 repetitions (3 second rest between repetitions).

Correct technique:
- ✓ Arms and chest off the ground
- ✓ Neck straight with eyes to the ground
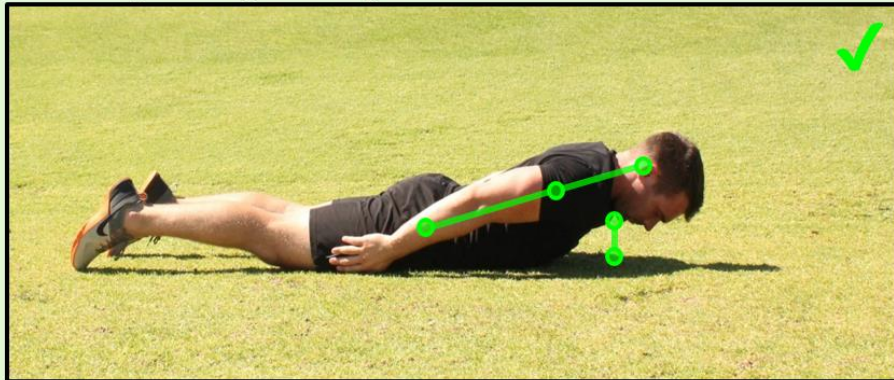
Incorrect technique:
- ✗ Hyperextending the low back

When to progress to the next stage?

➡ If you can complete the prescribed volume with correct technique and have performed at least 2 weeks (4 sessions)

➡ After completing 2 weeks (4 sessions)

Stage 2

Trunk extensor endurance (arm and opposite leg up)

Description: Place one arm out in front of the body, lift the leg on the opposite side and lift the chest approximately 5cm off the ground. Hold the position for 10 seconds and alternate the arm and leg between repetitions.

Volume: 10 repetitions (3 second rest between repetitions).

Correct technique:
- ✔ Keep one arm, one leg and the chest off the ground
- ✔ Keep the neck straight with eyes to the ground
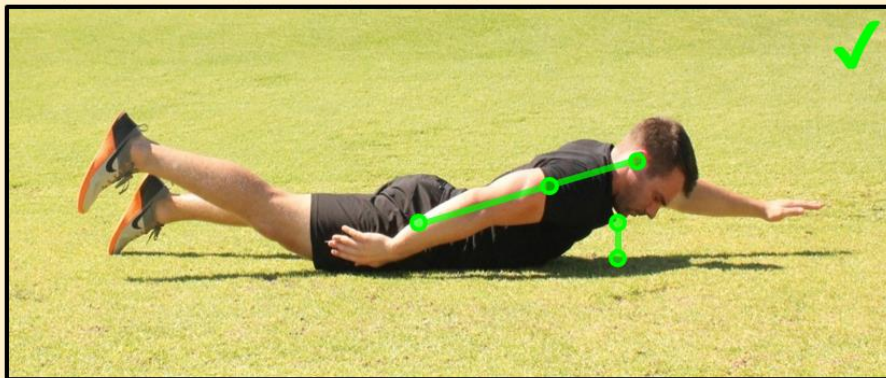
Incorrect technique:
- ✘ Hyperextending the low back
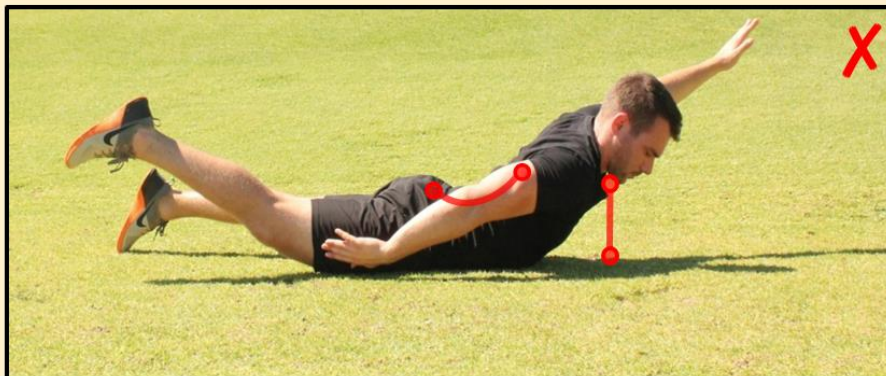
When to progress to the next stage?

➡ If you can complete the prescribed volume with correct technique and have performed at least 3 weeks (6 sessions)

➡ After completing 3 weeks (6 sessions)

Stage 3

Trunk extensor endurance (arms and legs up)

Description: Place both arms out in front of the body, lift both legs and lift the chest approximately 5cm off the ground. Hold the position for 10 seconds.

Volume: 10 repetitions (3 second rest between repetitions).

Correct technique:
- ✓ Keep the arms, the legs and the chest off the ground
- ✓ Keep the neck straight with eyes to the ground

Incorrect technique:
- ✗ Hyperextending the low back
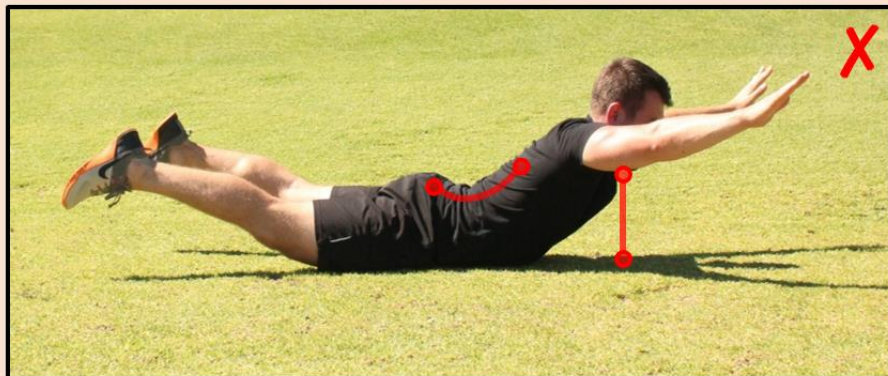
What should I do next?

If you can complete the prescribed volume with correct technique for this stage, you should aim to maintain this throughout the season. You could make this exercise more challenging by holding a cricket bat while you perform this exercise.

Appendix F Ethics Documentation

Thursday, 11 August 2016

Dr Alasdair Dempsey
School of Psychology and Exercise Science
Murdoch University

Dear Alasdair,

Project No.   2016/136
Project Title   Modifying risk factors for injury in adolescent cricket pace bowlers

Thank you for addressing the conditions placed on the above application to the Murdoch University Human Research Ethics Committee. On behalf of the Committee, I am pleased to advise the application now has:

OUTRIGHT APPROVAL

Approval is granted on the understanding that research will be conducted according the standards of the *National Statement on Ethical Conduct in Human Research* **(2007)**, the *Australian Code for the Responsible Conduct of Research* **(2007)** and **Murdoch University policies** at all times. You must also abide by the **Human Research Ethics Committee's standard conditions of approval (see attached).** All reporting forms are available on the Research Ethics and Integrity web-site.

I wish you every success for your research.

Please quote your ethics project number in all correspondence.

Kind Regards,

Dr. Erich von Dietze
Manager
Research Ethics and Integrity

cc: Dr Jeffrey Hebert; Dr Brendan Scott; Mitchell Forrest

Appendix G Published Manuscripts

Risk Factors for Non-Contact Injury in Adolescent Cricket Pace Bowlers: A Systematic Review

Mitchell R. L. Forrest[1] · Jeffrey J. Hebert[1,2] · Brendan R. Scott[1] ·
Stefano Brini[1,3] · Alasdair R. Dempsey[1]

Abstract

Background Adolescent cricket pace bowlers are prone to injury. Recognising the risk factors for non-contact injury in this population will aid future injury prevention strategies.

Objective To identify the risk factors for non-contact injury in adolescent cricket pace bowlers.

Methods We systematically searched PubMed, Cochrane Library, PEDro, SPORTDiscus, Embase, and the South African Journal of Sports Medicine to identify all experimental and observational studies reporting risk factors for non-contact injuries in pace bowlers (aged 12–19 years). The search syntax included terms relevant to cricket bowling, injury, and known risk factors for injury. The Newcastle-Ottawa Quality Assessment Scale and a modified Newcastle-Ottawa Quality Assessment Scale were used to assess the risk of bias in the cohort and cross-sectional studies, respectively.

Results Sixteen studies (five cross-sectional studies, 11 cohort studies) comprising 687 participants (96% male, 75% playing cricket in Australia) met the selection criteria and were included for qualitative synthesis. Three cross-sectional studies were rated as high risk of bias and two as very high risk of bias. For the cohort studies, three were rated as low risk of bias, and eight as high risk of bias. Injury was associated with bowling biomechanics (excessive lateral trunk flexion and pelvis/hip kinematics), reduced trunk endurance, poor lumbo-pelvic-hip movement control, and early signs of lumbar bone stress. Conflicting results were found by studies examining the mixed technique, bowling workload and quadratus lumborum asymmetry.

Conclusions The current systematic review identified a number bowling biomechanics and various neuromuscular deficiencies as risk factors for non-contact injury in adolescent pace bowlers. These factors may provide a useful target for future interventional research aiming to prevent injury in this population. Future studies should utilise prospective cohort designs, and ensure that participants are injury-free at baseline, confounding factors are well controlled and attrition rates are reported.

Registration This systematic review was registered a priori (PROSPERO, CRD42016043956).

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[2] Faculty of Kinesiology, University of New Brunswick, Fredericton, Canada

[3] Department of Psychology and Speech-Language Pathology, University of Turku, 20014 Turku, Finland

🖄 Springer

REVIEW ARTICLE

Injury Prevention Strategies for Adolescent Cricket Pace Bowlers

Mitchell R. L. Forrest[1,3] · Brendan R. Scott[1,3] · Jeffrey J. Hebert[1,2] · Alasdair R. Dempsey[1,3]

Abstract

Adolescent cricket pace bowlers are prone to non-contact shoulder, low back and lower-limb injuries. Exercise-based injury prevention programmes (IPPs) are effective for reducing non-contact injuries in athletes; however, a specific programme for adolescent pace bowlers has not been published. This paper therefore seeks to provide a rationale for the development of an exercise-based IPP specific for adolescent pace bowlers. It also outlines design principles and provides an example exercise programme that can be implemented at the community level. In addition, the paper addresses other injury prevention techniques concerned with the prescription of appropriate bowling loads and the modification of poor bowling biomechanics. Performing an exercise-based IPP before cricket training could reduce injury rates in adolescent pace bowlers. Eccentric strengthening exercises can be employed to target injuries to the posterior shoulder muscles, hip adductors and hamstring muscles. The risk of low back, knee and ankle injury could also be reduced with the inclusion of dynamic neuromuscular control exercises and trunk extensor endurance exercises. Other prevention strategies that need to be considered include the modification of poor bowling biomechanics, such as shoulder counter-rotation and lateral trunk flexion. Coaches and players should also aim to quantify bowling load accurately and coaches should use this information to prescribe appropriate individualised bowling loads. Specifically, players would benefit from avoiding both long periods of low load and acute periods when load is excessively high. Future evidence is needed to determine the effectiveness of the example programme outlined in this paper. It would also be beneficial to investigate whether the modification of bowling biomechanics is achievable at the non-elite level and if bowling load can be accurately measured and manipulated within a community-level population.

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[3] Murdoch Applied Sports Science Laboratory, Murdoch University, 90 South St, Murdoch, Perth, WA 6150, Australia

Key Points

Due to the non-contact nature of injuries in youth pace bowlers, exercise-based interventions should be able to reduce injury risk.

Injury prevention exercises for adolescent pace bowlers should aim to improve eccentric strength of the external shoulder rotators, increase hip adductor strength, improve eccentric hamstring strength, increase dynamic neuromuscular control of the lumbopelvic region/lower limbs, and increase trunk extensor endurance.

A holistic injury prevention programme for youth pace bowlers should also manage bowling load and ensure bowlers have appropriate bowling technique.

Δ Adis

Original research

Exercise-based injury prevention for community-level adolescent cricket pace bowlers: A cluster-randomised controlled trial

Mitchell R.L. Forrest [a,b,*], Jeffrey J. Hebert [a,c], Brendan R. Scott [a,b], Alasdair R. Dempsey [a,b]

[a] College of Science, Health, Engineering and Education, Murdoch University, Australia
[b] Murdoch Applied Sports Science Laboratory, Murdoch University, Australia
[c] Faculty of Kinesiology, University of New Brunswick, Canada

ABSTRACT

Objectives: To investigate if an exercise-based injury prevention program (IPP) can modify risk factors for injury in community-level adolescent cricket pace bowlers.
Design: Cluster-randomised controlled trial.
Methods: Eight cricket organisations (training two times per week and no previous involvement in a structured IPP) participated in this cluster-randomised trial. Participants were aged 14–17 years, injury free, and not currently performing a rehabilitation/exercise program. Cricket organisations (clusters) were block-randomised by computerised number generation into an intervention group (performed an eight-week IPP at training) or control group (continued their usual cricket activity). Participants were not blinded to group allocation. Strength, endurance, and neuromuscular control were assessed at baseline and follow-up. Treatment effects were estimated using linear mixed models.
Results: Sixty-five male adolescent pace bowlers (intervention n = 32 and control n = 33) were randomised. There were significant treatment effects favouring the intervention group for shoulder strength (90°/s) 0.05 (95% CI 0.02–0.09) N m/kg, hamstring strength (60°/s) 0.32 (95% CI 0.13–0.50) N m/kg, hip adductor strength dominant 0.40 (95% CI 0.26–0.55) N m/kg and non-dominant 0.33 (95% CI 0.20–0.47) N m/kg, SEBT reach distance dominant 3.80 (95% CI 1.63–6.04) percent of leg length (%LL) and non-dominant 3.60 (95% CI 1.43–5.78) %LL, and back endurance 20.4 (95% CI 4.80–36.0) seconds. No differences were observed for shoulder strength (180°/s) (p = 0.09), hamstring strength (180°/s) (p = 0.07), lumbopelvic stability (p = 0.90), and single leg squat knee valgus angle (dominant p = 0.06, non-dominant p = 0.15).
Conclusions: Exercise-based IPPs can modify risk factors for injury in community-level adolescent pace bowlers. Future research is needed to confirm if IPPs can also reduce injury risk in this population.
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Practical implications

- Exercise-based injury prevention programs can be easily implemented to modify some risk factors for injury in community-level adolescent pace bowlers.
- The improvements in shoulder strength (90°/s), hamstring strength (60°/s), hip adductor strength, and reach distance on Start Excursion Balance Test likely represent clinically important changes which could attenuate injury risk.
- Pace bowlers who do not perform injury prevention exercises throughout the season may increase their risk factors for injury.

1. Introduction

Cricket is a popular community-level sport in many Commonwealth countries, though it is associated with a risk of injury.[1] Pace bowlers are the most injury-prone group in youth cricket, with seasonal incidence rates of approximately 26%.[1] Most of their injuries are non-contact and generally to the low back, shoulder and lower limb.[1] Lumbar stress fractures are the most concerning injury in youth pace bowlers (one-year incidence 12%) and typically cause players to miss several months of cricket.[2]

A number of risk factors for these injuries have been identified and these include; poor bowling biomechanics, inappropriate bowling load, and neuromuscular deficiencies (e.g., reduced muscular strength, neuromuscular control, and muscular endurance).[3] While earlier studies have attempted to change bowling biomechanics[4] and there are published guidelines for bowling load,[5] there is minimal published literature which has attempted

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