The Presence of Known Biomechanical Risk Factors for Low Back Injuries in Junior Cricket Fast Bowlers

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Herath Mudiyanselage Sajeewa Udana Bandara

B.Sc. (Hon.) Special in Sport Science and Management

School of Environmental and Life Sciences

Faculty of Science

University of Newcastle

AUSTRALIA

Statement of Originality

I hereby certify that the work embodied in the thesis is my own work, conducted under normal supervision. The thesis contains no material which has been accepted, or is being examined, for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made. I give consent to the final version of my thesis being made available worldwide when deposited in the University's Digital Repository, subject to the provisions of the Copyright Act 1968 and any approved embargo.

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Date Signed

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List of Abbreviations

°	Degrees
>	Greater than
<	Less than
%	Percent
±	Plus or minus
*	Indicates significant different results
2D	Two-dimensional
3D	Three-dimensional
AH	Arm horizontal
ANOVA	Analysis of variance
Ant	Anterior
ASIS	Anterior superior iliac spine
AV	Arm vertical
BFA	Back foot angle
BFC	Back foot contact
BIC	Back foot initial contact
BMC	Bone mineral content
BMD	Bone mineral density

BR	Ball release
Bul	Bulging
BM	Body mass
CI	Confidence interval
CT	Computed tomography
cm	Centimetre
cm^2	Centimetre squared
CSA	Cross-sectional area
d	Cohen’s d
DXA	Duel-energy X-ray absorptiometry
D.Degen	Disc degeneration
EMG	Electromyography
GRF	Ground reaction force
g	Gram
F_{ant}	Anterior force
FFC	Front foot contact
F_{lat}	Lateral force
F_{med}	Medial force
F_{post}	Posterior force
FTO	Front foot-ground take off

F_v	Vertical force
HR	High risk
ICC	International cricket council
Inj	Injured
kg	Kilogram
$km \cdot h^{-1}$	Kilometres per hour
Lat	Lateral
LJ	Left joint
LQ	Lower quarter
LF	Lateral flexion
LBP	Low back pain
m	Metre
m^2	Metres squared
min	Minute
mm	Millimetre
$m \cdot s^{-1}$	Metres per second
MRI	Magnetic resonance imaging
n	Sample size
N	Newtons
N/AD	Not addressed

N/AP	Not applicable
NR	Not reported
NS	Not stated
NSW	New South Wales
NTL	No time loss
NM	Newton metres
OSICS	Orchard sports injury classification system
p	Alpha
Post	Posterior
PS	Pedicle sclerosis
PSIS	Posterior superior iliac spine
QL	Quadratus lumborum
r	Pearson’s product-moment correlation coefficient
RJ	Right joint.
ROM	Range of motion
SA	Shoulder alignment
SCR	Shoulder counter rotation
SEBT	Star excursion balance test
SSA	Shoulder separation angle
SLDS	Single-leg decline squat

Spon	Spondylolisthesis
SPSA	Shoulder pelvis separation angle
TL	Time loss
Ver	Vertical
W	Watt
WL	Work load
y	Years

Abstract

Introduction: Injury prevalence rates of cricket fast bowlers increase over time. Fast bowlers lose 16% of potential playing time due to injury, while all other playing positions in cricket lose 5% of potential playing time. Most of the injuries of cricket fast bowlers occur in the lumbar region of the spine. Young fast bowlers have a higher risk of injury to the lower back compared to adult cricket fast bowlers and 37% - 55% of injuries among junior fast bowlers are in the lower back. Researchers have reported that bowling action is one of the main factors associated with low back injuries, with the mixed bowling action identified as having the highest-risk of injury. Hence, the first aim of this thesis is to examine biomechanical factors associated with low back pain and injury in fast bowlers through a systematic review of the literature. Secondly, a biomechanical analysis of junior cricket fast bowlers will be performed to established the presence of identified risk factors among junior fast bowlers, as well as to measure bone health and muscle symmetry.

Systematic review

Method: Seven electronic bibliographic databases including MEDLINE, EMBASE, SCOPUS, COCHRANE LIBRARY, WEB OF SCIENCE as well as SPORTDISCUSS were used as primary search sources. Eleven key words were used with three different combination formats in the electronic data bases searched. Three different factors including participant characteristics, biomechanical analysis, and the currency of the study were considered for the inclusion criteria. Methodological quality assessment of included articles was conducted using the McMaster University Guidelines and Critical Review Form for Quantitative Studies. Biomechanical data were extracted from the studies and summarised.

Results: Six articles were selected for the systematic review. All six were moderate to good quality according to critical appraisal scores, which ranged from 9 to 11 (Mean 9.5) out of 15. Three studies reported 3D biomechanical data and the other three studies reported 2D biomechanical data. Only one study investigated female participants, while all other studies investigated male participants. The mean age of the participants ranged from 13 to 27 years. Three studies out of six investigated junior state/club level fast bowlers and the other three investigated senior elite level fast bowlers. Out of these six included studies, only four studies used force plates to report cricket fast bowling kinetics. Higher lumbar lateral flexion power, lumbar lateral flexion moment, as well as lumbar flexion moments were the identified kinetic factors associated with lower back injuries. However, some conflicting findings were noticed, as three studies out of four which reported kinetic results did not report any association of the above-mentioned kinetic factors with lower back injuries. Higher hip flexion, shoulder alignment at back foot contact and at ball release, thorax lateral flexion at front foot contact and ball release, range of thorax lateral flexion, pelvis rotation at ball release and more importantly shoulder counter-rotation were identified kinematic factors that were associated with lower back injuries. However, similar to kinetic factors, there were some conflicting results reported, including one study that did not report any significant relationship between shoulder counter rotation and low back injuries.

Conclusion: Both kinetic and kinematic factors associated with low back injuries were identified through the systematic review. However, some conflicting findings were reported, indicating that further research is needed to investigate the validity of the identified biomechanical risk factors.

Experimental study

Method: Eleven junior male representative fast bowlers (mean age 13.8 ± 0.6 y, mean height 173.9 ± 5.3cm, mean weight 63.5 ± 5.7kg) were recruited from the Central Coast and Newcastle area, NSW, Australia. Each participant completed a spell of five overs at game pace. Three–dimensional (3D) kinematics (500Hz) and ground reaction forces (2000Hz) of the bowling action were recorded during the delivery stride and analysed in Visual 3D software. All participants underwent a whole-body Dual-energy X-ray absorptiometry (DXA) scan to examine bone health and muscle distribution.

Results: The majority (63.6%) of the junior fast bowlers used the mixed bowling action and the only other action used was the semi-open bowling action (36.7%). Biomechanical risk factors for lower back injuries, as identified in the systematic review, were observed in the entire study cohort. Greater shoulder counter rotation, shoulder alignment at back foot contact and ball release, thorax lateral flexion at front foot contact and ball release, range of thorax lateral flexion, pelvis rotation at ball release and hip flexion are identified kinematic factors, which were significantly higher in the mixed bowling action group compared to the semi-open bowling action group. Furthermore, higher lumbar lateral flexion power, lumbar lateral flexion moment and lumbar flexion moment are identified kinetic factors, which were significantly higher in the mixed bowling action group compared to the semi-open bowling action group. No significant differences were observed for bone mineral density or lean mass between bowling action groups in any region of the body. Furthermore, no differences in bone mineral density and lean mass were found between the dominant and non-dominant side of the body.

Conclusion: Although several studies identified the mixed bowling action as a high-risk bowling action for low back injuries, the majority of the junior fast bowlers in this study used the mixed action. These junior bowlers also demonstrated several identified kinematic and kinetic risk factors for lower back injuries. It is alarming that 63.6% of junior fast bowlers select the mixed bowling action, as this may lead to minor to severe injuries and potentially early dropout. It appears better education is needed for coaches and athletes to alert them to higher risk of lower back injuries for bowlers using the mixed action.

Chapter 1

Introduction

1. Chapter 1. Introduction

1.1. Rationale

The game of cricket is considered a low injury risk sport with only 5% of elite athletes being unavailable for match play due to an injury at any given time (Johnson, Ferreira, & Hush, 2012; Worthington, King, & Ranson, 2013). Nevertheless, the fast bowling action performed by cricketers within the game has been identified as one of the non-contact activities most likely to lead to injury (Bartlett, Stockill, Elliott, & Burnett, 1996). A recent review of the literature concludes that the prevalence rate of low back injuries in all fast bowlers ranged from 11% to 67% (Johnson et al., 2012). A study conducted over a 10-year period (1995-2005) with Australian fast bowlers in national and state teams reported that injury prevalence rate increased over time and that fast bowlers lost 16% of potential playing time due to injury, which was much higher than the 5% of playing time lost for all other playing positions (Orchard, James, & Portus, 2006). Like their adult counterparts, adolescent fast bowlers are also vulnerable to low back injuries (Bayne, Elliott, Campbell, & Alderson, 2016). It is a serious cause for concern when such injuries are diagnosed among junior cricketers, especially during the critical period of growth and musculoskeletal maturation (Logsdon, 2007; Schaefer, O'Dwyer, Ferdinands, & Edwards, 2018). It is important to note that 24% of junior bowlers (mean age 13.3y) have lumbar spinal abnormalities on magnetic resonance imaging (MRI) (Elliott & Khangure, 2002; Schaefer et al., 2018), many of which may be linked to recurring clinical symptoms and ultimately, in the worst cases, may be career ending. Given the high prevalence of low back injuries in physically developing youth cricketers further research is needed investigating risk factors in cricket fast bowling to facilitate early correction of technique in an attempt career to avoid future injury consequences.

1.2. Background

1.2.1. Injuries in cricket

The game of cricket is characterised by highly complex and vigorous activities such as batting, bowling, and running, throwing, catching, as well as jumping and diving. These actions are physically demanding and it is therefore not surprising to see overuse and impact injuries among cricketers (Pardiwala, Rao, & Varshney, 2018). Numerous studies have investigated injuries in cricket (see Table 1.1). According to Stretch (2003) cricket cannot be regarded as a sport with only "moderate injury risk", as cricketers are vulnerable to a wide variety of injuries at all stages of the season. Cricket has been identified as the 5th ranked sport for seniors (at 7.3%) and 8th ranked sport for juniors (at 3.7%) presenting with injuries to hospital emergency departments in Australia (Finch, Ozanne, & Williams, 1995; Orchard, James, Alcott, Carter, & Farhart, 2002). Injuries in cricket consist primarily of concussions, contusions, and lacerations (Stretch, 2003). In modern day cricket, hamstring strain has been identified as one of the most common injuries, while the lumbar stress fracture in fast bowlers is recognised as the most severe injury (Pardiwala et al., 2018). Fast bowlers have the highest number of time-loss injuries, while batters have the highest number of non-time loss injuries (Ranson, Hurley, Rugless, Mansingh, & Cole, 2013). The relatively higher injury incidence in fast bowlers was also shown by Stretch (2003), who reported that within 812 injuries sustained by 436 cricketers 41.3% resulted from bowling, 28.6% from fielding and wicket-keeping, and only 17.1% from batting. Moreover, it is critical to state that nearly 50% of injuries in cricketers occurred during matches and out of those injuries nearly 50% happened while bowling (Orchard et al., 2006). A review by Elliott (2000) cited that injury risk in fast bowling is higher in school-age cricketers (47.4%) (Stretch, 1995) compared with senior A-grade or provincial-level cricketers (42%) (Stretch, 1992). These findings indicate that bowlers in cricket are more prone to injuries compared to all other playing positions and that injuries start from a young age.

1.2.2. Prevalence of lower back injuries in fast bowlers

Lower back injuries have been identified as the injury causing the greatest time loss among professional fast bowlers in cricket (Ferdinands, Stuelcken, Greene, Sinclair, & Smith, 2010a; Orchard et al., 2002; C. A. Ranson, A. F. Burnett, M. King, N. Patel, & P. B. O'Sullivan, 2008). Orchard et al. (2006) showed that fast bowlers lost about 16% of potential playing time due to injuries, while this was less than 5% for all other playing positions. Several studies have identified that lumbar spine injuries are most prevalent among cricket fast bowlers, with a reported prevalence rate of between 11% - 67% (Elliott, Hardcastle, Burnett, & Foster, 1992; Gregory, Batt, & Kerslake, 2004; C. A. Ranson et al., 2008). Epidemiological studies conducted in major cricket playing countries, such as Australia (Orchard et al., 2006), South Africa (Stretch, 2003) and the West Indies (Mansingh, Harper, Headley, King-Mowatt, & Mansingh, 2006), all highlight that fast bowlers have a high risk of lower back injuries and that they are most vulnerable to not only traumatic but also overuse injuries (Glazier, 2010; Hecimovich, 2017). For example, it was reported that out of 26 elite Australian female fast bowlers more than half (n= 14, 54%) reported a history of low back pain (Stuelcken, Ferdinands, & Sinclair, 2010).

Compared to adult cricketers, young fast bowlers have a higher risk of injury to the back (Hecimovich, 2017). According to Dennis, Finch, and Farhart (2005), 25% of junior fast bowlers were diagnosed with overuse injuries during the season and 63% of these overuse injuries were back injuries. Overall it has been reported that 37% to 55% of injuries among junior fast bowlers are in the lower back (Crewe, Elliott, Couanis, Campbell, & Alderson, 2012; Davies, Randt, Venter, & Stretch, 2008).

1.2.3. Types of lumbar spinal injuries in fast bowlers.

Of all overuse injuries, lumbar spinal injuries have been identified as the greatest cause of lost playing time for cricket fast bowlers compared to all other injuries (Bayne et al., 2016). Due to the nature of the fast bowling action, bowlers repetitively laterally flex the spine to the non-dominant side to the bowling arm at the delivery stride. Hence a lumbar stress fracture on the non-dominant side to the bowling arm is the most prevalent injury among fast bowlers (Crewe, Campbell, Elliott, & Alderson, 2013a; Orchard et al., 2006; Worthington et al., 2013). The prevalence rate of lumbar stress injuries in cricket fast bowlers is up to 67% (Johnson et al., 2012). Several injuries that impact the lumbar spine have been identified in fast bowlers, such as spondylolysis, spondylolisthesis, pedicel sclerosis as well as intervertebral disc degeneration (Crewe et al., 2013a; Elliott et al., 1992; Portus, Mason, Elliott, Pfitzner, & Done, 2004).

In junior cricket fast bowlers some prospective studies report a high prevalence of lumbar spondylolysis at the rate of 11% within a season (Foster, John, Elliott, Ackland, & Fitch, 1989) and 24% over a four-year period of time (Engstrom & Walker, 2007). Junior fast bowlers are also at risk of developing intervertebral disc degeneration (Crewe et al., 2012). In a cohort with a mean age of 13.6 years, 25% demonstrated at least one lumbar radiographic disc abnormality following MRI imaging. Surprisingly within the same cohort, the incidence of abnormality had increased up to 58% two and half years later (Burnett et al., 1996). Moreover, an observational study conducted by Crewe et al. (2012) in 46 asymptomatic fast bowlers aged 13 to 18 years showed that 33% (n = 15) of fast bowlers presented with at least one pars interarticularis abnormality and at least one lumbar degeneration was observed within 35% (n = 16) of participants. Moreover, the rate of prevalence increased with each of the following age categories (29% - U15, 33% - U17, and 43% U-19) and out of the 16 participants with disc degeneration 12 participants presented a disc bulge.

Several studies have investigated the consequences of these low back injuries among cricket fast bowlers, especially among junior fast bowlers. The continued loading on the spine due to fast bowling actions throughout the adolescent developing years may cause serious consequences for juniors, such as long-term injuries like spondylolysis, spondylolisthesis, as well as pedicle sclerosis, and these fast bowlers may end up with thoracolumbar degenerative diseases in later life (Annear, Chakera, Foster, & Hardcastle, 1992). Out of the different types of spondylolysis, dysplastic congenital lesions and isthmic lesions, which present as chronic injuries resulting from repetitive loading of pars interarticularis, have been identified as most commonly occurring among young fast bowlers (Crewe et al., 2012; Standaert & Herring, 2000). To address the serious negative health consequences resulting from repeated fast bowling, cricketing governing bodies have implemented prevention strategies, such as managing bowling work-load by restricting the numbers of balls bowled in a bowling spell (Schaefer et al., 2018) and coaching interventions that emphasize the importance of proper bowling technique and physical preparation, as well as encouraging bowlers to adopt a more front-on or side-on bowling action (Elliott & Khangure, 2002).

Table 1. 1 Overview of injuries in cricket

Author (Year)	Participant details	Study duration	Injury definition	Injury surveillance	Injury incidence	Injury mechanism	Injury prevalence
Dennis, Farhart, Clements, and Ledwidge (2004)	n = 12 Gender = male Mean age = 25 (21-37 y) Country: Australia	1 year	A condition that affected availability for team selection, limited performance during a major match or required surgery.	Sports Medicine Professionals	7 reported with 9 injuries. Recurrence injuries = 0 The frequency of bowling is significantly higher among injured people than non-injured people (p<0.01)	Muscle Strain and Stress Fractures The risk of sustaining injury was 4.5 times higher for bowlers who bowled 5 or more days in any 7 days.	
Hulin et al. (2014)	n = 28 Gender = male Completed 48 individual seasons over 6 years. Mean age 26 ± 5 y Country: Australia	6 years of data	Any non-contact injury that resulted in a loss of either match-time or greater than one training session over a 1-week period.	Medical Staff.	The relationship between external workloads in the current week and Injuries is significant (p=0.0001) No relationship between acute external workload and injury (p=0.172) Higher Chronic external workload in both current week (p=0.002) and subsequent week(p=0.017) was associated with lower injury risk		

Author (Year)	Participant details	Study duration	Injury definition	Injury surveillance	Injury incidence	Injury mechanism	Injury prevalence
Mansingh et al. (2006)	National n = 33 Domestic n = 162 First Class n = 128 Gender = male Age = 18-37 y Country: West Indies	18 months	Any injury or other medical condition that Either: (1) prevents a player from being fully available for selection in a match or (2) during a major match, causes a player to be unable to bat, bowl or keep wicket when required by either the rules or the team's captain. (The definition of cricket injury)	Medical Staff or Physiotherapist	Injuries = 79 Missed part of match = 50 First time injuries- 8-% Recurrent injuries - 10% Sustained injuries – 10% Fast bowlers injuries - 40% Muscle strain – 26% Ligament strain – 12% Stress fractures -12% Other fracture -10%		Lumbar area – 20% Phalanx - 22% 57% of injuries of fast bowlers were in the lumbar area
Olivier, Stewart, Olorunju, and McKinon (2015)	n = 32 Injury free fast bowlers Gender = male Mean age = 21. 8 ± 1.8 y Country: South Africa	N/S	"LQ injury" - bowlers who sustained a lower quarter (LQ) (low back and lower limb) injury "No LQ injury" - who did not sustain an injury is referred to as "no LQ injury."	N/S	Sustained previous injuries - 88% (n= 28) Sustained low back injury - 14% (n = 4) Injuries sustained during the cricket season 53% (n = 17). 24% (n = 4) sustained a low back injury	Previous sustained during bowling = 64% Sustained during the season during bowling = 94% SEBT posterior medial reach direction was poor for the LQ injury group.	Previous sustained ; One area – 32% (9) Two areas – 39% (11) Three or more – 29% (8) Sustained during the season: One area – 41% (7) Two areas – 29% (5) Three or more – 29% (5)

Author (Year)	Participant details	Study duration	Injury definition	Injury surveillance	Injury incidence	Injury mechanism	Injury prevalence
Orchard et al. (2006)	Gender = male Seven squads (n=25 per squad) including six from states and National team. Country: Australia	Ten years 1995-2005 Retrospectively 3 years (1995-1998) Prospectively 7 years (1999-2005)	The definition of cricket injury	Medical Staff or physiotherapist	Identified injuries – 886 First time injuries – 818 (92%) Injuries during bowling – 209 (25.5%)		Low back region :0.8% - 3.1% Groin/Buttock/Thigh:0.7%-2% Neck region: 0.0%-0.1%
Orchard et al. (2015)	n= 235 Gender = male Experience of over 15 seasons Country: Australia	5 to 28 days	Based on definition of Cricket injury. Injuries which happen during batting or fielding were not considered.	N/S Injuries were coded with OSICS-V.9 system Subcategories of injuries: Muscle/ Bone Stress/ Tendon or joint injuries.	Muscle injuries – 336 Tendon injuries – 131 Bone stress – 120 Joint injuries – 78	Workload effect: Tendon (High Risk) – High Acute Workload (≥ 50 overs) and High Previous Season WL (≥ 400 overs) Bone (HR) – Medium term WL (≥ 150 overs) Muscle – no effect Joints (HR) - High previous season WL (≥ 400 Overs) and high career WL (≥ 3000)	Muscles: Hamstring, quadriceps, calf, adductor, side strains Tendon: Rotator cuff, patellar, Achilles and groin tendon injuries Bone: lumbar, shin and foot Joint: knee, ankle and lumbar joint pathologies
Ranson et al. (2013)	n = 76 Gender = male four test playing nations and one associate nation (Sri Lanka, South Africa, Bangladesh Pakistan, and Zimbabwe)	3 months (Feb – April 2011)	Both time loss and non-time loss injuries	ICC trained medical staff.	New injuries - 120 Time loss injuries - 23 (19%) None time loss injuries -97 (81%) Injuries to fast bowlers- 41 (19%) Time loss injuries 10 (43%) None time loss injuries 31 (40%)	Highest TL – acute sprain or strain 10 (43%) Highest NTL – cumulative micro-trauma 32 (33%)	Highest TL injured area is thigh – 5 (21%) then hand and lumbar – 4 (17%) Highest NTL injured area is lumbar – 16 (16%) then thigh – 14 (15%) Tournament injury prevalence for fast bowlers – 5.2% Match injury prevalence for fast bowlers – 4.6 %

Author (Year)	Participant Details	Study Duration	Injury Definition	Injury Surveillance	Injury incidence	Injury Mechanism	Injury prevalence
Stretch (2001)	n = 160 Gender = male Country: South Africa	2 year (2 seasons) S_1-Season 1 S_2-Season 2	Any pain that occurred which prevented the player from completing that particular match, practice or training session and caused the player to seek medical attention.	Medical staff or physiotherapist	injuries sustained – 285 1.61 injuries per player Acute – 60.3% Chronic 16.6% Acute on chronic 23.1% First-time injuries 61%		Lower limbs 49.9% Back and trunk 24.7% Upper limbs 20.4% Head, neck and face 5%

BFC: Back foot contact, FFC: Front foot contact, HR: High risk, ICC: International cricket council, LQ: Lower quarter, N/S: Not stated, NTL: No time loss , OSICS: Orchard sports injury classification system, ROM: Range of motion, SCR: Shoulder counter rotation, SEBT: Star excursion balance test, TL: Time loss, WL: Workload

1.3. Risk factors associated with low back injuries in fast bowlers

As shown in the previous sections lumbar spine injuries are prevalent in fast bowlers and may have severe career ending consequences, so it is important to investigate the risk factors associated with low back injuries in fast bowlers in order to implement necessary programming that lowers injury risk in this population. A review by Johnson et al. (2012) showed moderate evidence for overuse as a risk factor for low back injuries. Furthermore, as also shown in section 1.2, it was suggested that younger fast bowlers (under the age of 20 years) may be at higher risk than adults (Johnson et al., 2012). The strongest evidence, however, was shown for the bowling action, with the mixed action, in particular, strongly associated with low back injuries. The fundamental bowling movement plays a major role in kinetics and kinematics of the particular technique. Hence numerous studies have identified certain bowling actions as dominant factors that place fast bowlers at high risk of low back stress injuries (Bayne et al., 2016; Ferdinands et al., 2010a; Portus et al., 2004; Stuelcken et al., 2010) due to different kinetic and kinematic factors. At the same time, the mechanical loading associated with the fast bowling action may have a positive effect on bone health, including bone mineral density (Micklesfield, Gray, & Taliep, 2012). Finally, it has been suggested that future research should focus on the association between lumbar muscle asymmetries and low back injuries in adults (Johnson et al., 2012). The following sections will, therefore, provide further detail on bowling actions, bone health and muscle symmetry in fast bowlers.

1.3.1. Fast bowling technique

Fast bowlers in cricket have been categorized into two subcategories (fast and medium-fast) based on their bowling velocity (Johnstone et al., 2014). Bowlers who can manage an average bowling speed in excess of 145 $km.h^{-1}$ are classified as fast and those who bowl with speeds between 129 $km.h^{-1}$ to 145 $km.h^{-1}$ are classified as medium fast (Glazier, Paradisis, & Cooper, 2000). To restrict the reaction time of the batsman, all adult fast bowlers attempt to deliver the ball at a speed greater than 145 $km.h^{-1}$ (Schaefer et al., 2018; Worthington et al., 2013). Bowling action classification is an important aspect to consider when discussing the biomechanics of cricket fast bowling. The fast bowling action has been classified into four categories as front-on, semi-on, side-on and mixed action types (Portus et al., 2004). This classification of bowling actions has been mainly based on shoulder and pelvis kinematics across the transverse plane at the delivery stride (Ferdinands, Kersting, & Marshall, 2014; Portus et al., 2004), such as shoulder girdle alignment at the back foot contact (Worthington, King, & Ranson, 2013a). Many studies have shown that there is a significant impact of bowling action on the risk of lower back injuries (Burnett et al., 1996; Hardcastle, 1991; Portus et al., 2004). To classify the bowling action researchers have used different threshold criteria (Table 1.2). An early convention system introduced by Elliott, Davis, Khangure, Hardcastle, and Foster (1993a) included shoulder alignment, back foot angle and shoulder counter rotation. Later a similar convention system was proposed by Burnett, Elliott, and Marshall (1995) without the back foot angle criterion, but this system included the new parameters of shoulder alignment, pelvis shoulder separation angle and shoulder counter rotation. Portus et al.(2000) used similar criteria to Elliott et al. (1993a) in their first study, but slightly changed the threshold criteria of back foot angle and shoulder counter rotation. In their next study Portus et al. (2004) included shoulder alignment, pelvis shoulder separation angle and shoulder counter rotation, but excluded back foot angle criteria (see Table 1.2). Figure 1.1 demonstrates the angle convention system used by Portus et al. (2004) to classify action types, where shoulder and hip alignment angles are measured with respect to a vector running from the front to rear shoulder and hip joint starting from 180º to 270º. Ferdinands, Kersting, Marshall, and Stuelcken (2010) proposed a new alignment angle system, which defines shoulder and hip alignment from the orientation of a vector running rear to front shoulder and hip joint resulting in measurements from 0º to 90º (Figure 1.2).

Figure 1.1 Conventional alignment angle system for a right-hand bowler which is used to measure alignment angle from the orientation of a vector running from left joint centre (LJ) to right joint centre (RJ) with respect to the X - axis. Figure extracted from Ferdinands et al. (2010)

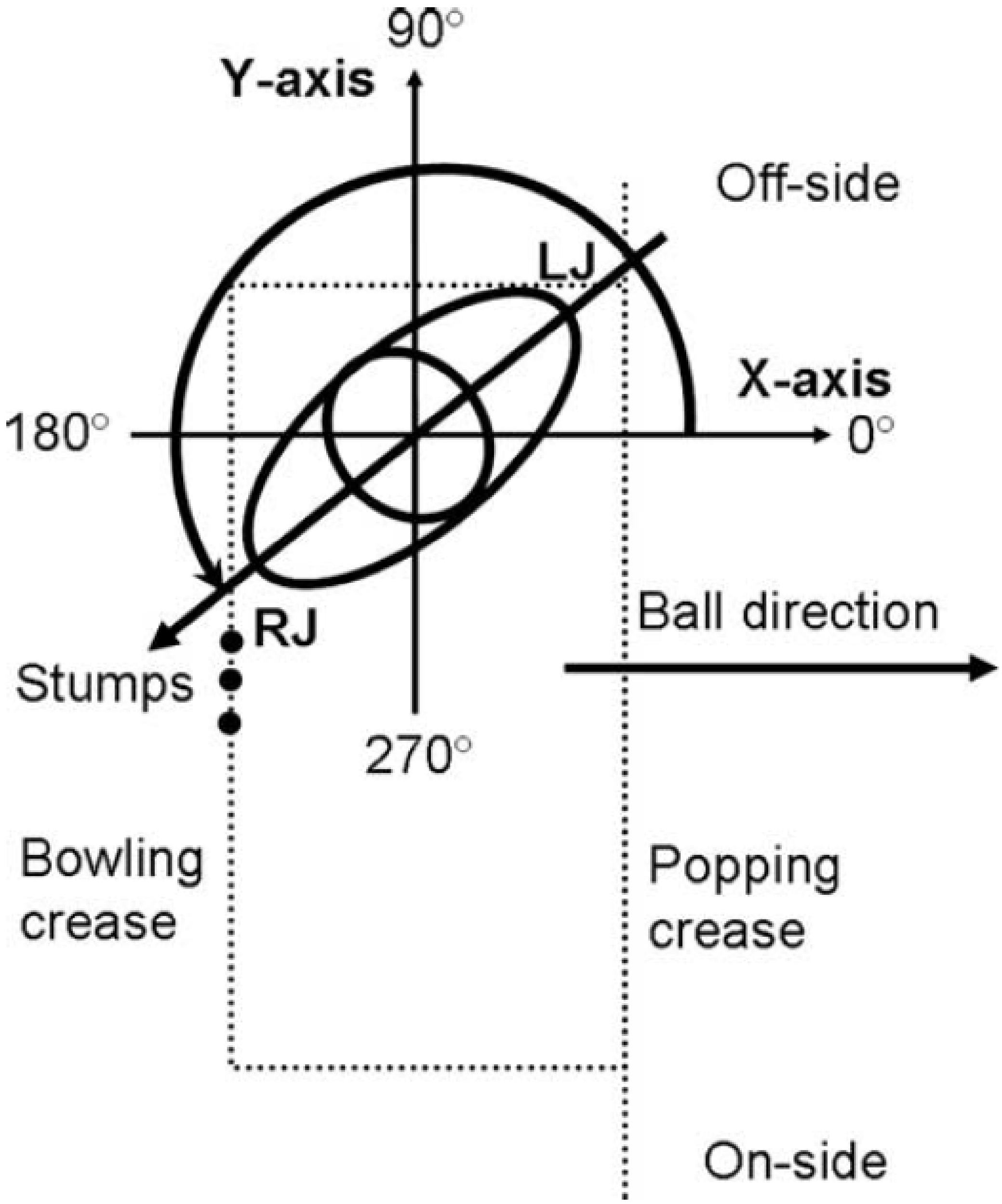

Figure 1.2 New conventional alignment angle system for a right-hand bowler which is used to measure alignment angle from the orientation of a vector running from right joint centre (RJ) to left joint centre (LJ) with respect to the X - axis. Figure extracted from Ferdinands et al. (2010)

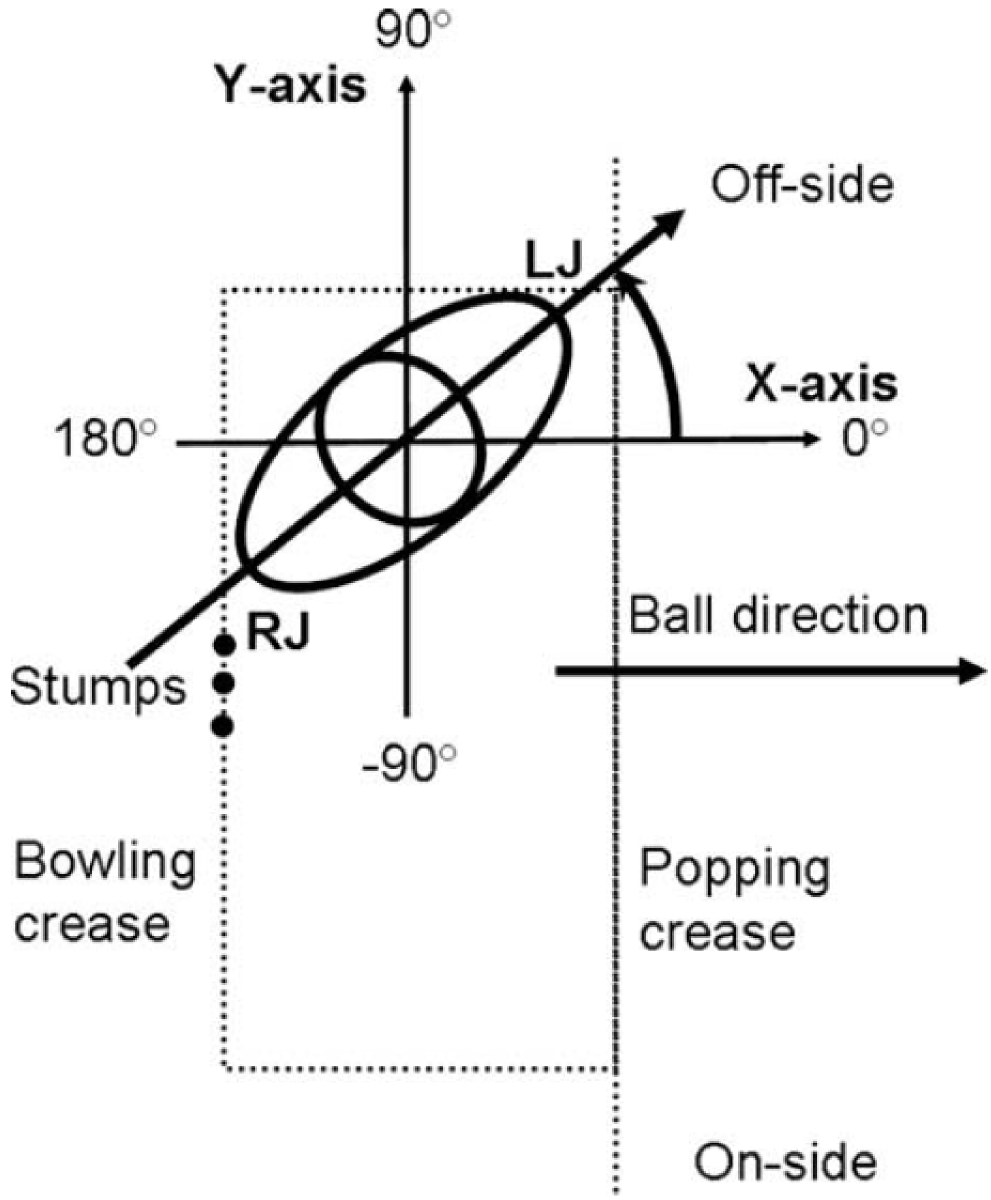

Table1.2 Bowling action classification systems

	Side-on				Front-on				Semi-open				Mixed			
	SCR	SA	SPSA	BFA	SCR	SA	SPSA	BFA	SCR	SA	SPSA	BFA	SCR	SA	SPSA	BFA
Elliott et al (1993)	N/AP	$\leq 190^o$	N/AP	$\leq 280^0$	N/AP	$>190^0$	N/AP	BFA$>280^0$	N/AP	N/AP	N/AP	N/AP	SCR$>10^0$	SA$>190^0$	N/AP	N/AP
Burnett et al (1995)	N/AP	$< 200^0$	N/AP	N/AP	N/AP	$>200^0$	N/AP	N/AP	N/AP	N/AP	N/AP	N/AP	SCR$>20^0$	SA$>190^0$	SPSA$>20^0$	N/AP
Portus et al (2000)	N/AP	$<190^0$	N/AP	$<290^0$	N/AP	$>190^0$	N/AP	BFA$>290^0$	N/AP	N/AP	N/AP	N/AP	SCR$>40^0$	SA$>190^0$	N/AP	N/AP
Portus et al (2004)	$<30^0$	$<210^0$	$<30^0$	N/A	$<30^0$	$>240^0$	N/AP	N/AP	SCR$<30^0$	$210^0<$SA$<240^0$	N/AP	N/AP	SCR$>30^0$	N/AP	SPSA$>30^0$	N/AP
Ferdinands (2010)	$<30^0$	$<25^0$	N/AP	N/A	$<30^0$	$>50^0$	N/AP	N/AP	SCR$<30^0$	$25^0<$SA$<50^0$	N/AP	N/AP	SCR$>30^0$	N/AP	SPSA$>30^0$	N/AP

BFA: Back foot angle, N/AP: Not applicable SA: Shoulder alignment, SCR: Shoulder counter rotation, SPSA: Shoulder pelvis separation angle, (Both SA and BFA is at back foot contact)

- Shoulder alignment: The angle that is created from the line running between rear to front shoulder joint centres in respect to the x axis.
- Pelvis alignment: The angle that is created from the line running between rear to front hip joint centres in respect to the x axis.
- SPSA: SA minus PA
- SCR: The SA angle at the BFC minus the minimum SA angle between BFC to FFC (most side-on position).
- BFA: The angle that is created from the line running from heel to toe of the back-foot in respect to the global X axis.

According to a review by Bartlett et al. (1996), the side-on bowling action is considered as the most effective and correct action by researchers and coaches. The run-up speed is relatively slow at the beginning of the delivery stride. The back foot is placed parallel to the popping crease with the shoulder pointed down towards the wicket, which creates an angle of approximately 180º between the wickets and the line joining the shoulders (Bartlett et al., 1996). Unlike the side-on action, the front-on action has a higher run-up speed, the back foot is placed pointing in the same direction as the ball travels, and the chest opens more with the shoulder at an angle which significantly exceeds 180^0. Most of the West Indian fast bowlers use this front on bowling action (Bartlett et al., 1996; Elliott et al., 1992). As the name suggests, the mixed action bowling technique is a combination action of both side-on and front-on bowling actions. In the mixed action, bowlers demonstrate front-on characteristics in the foot and shoulder alignments at the back foot contact and then during the delivery stride the shoulder alignment changes to the more side-on position (Bartlett et al., 1996; Elliott, Hardcastle, Khangure, & Burnett, 1993).

Among all bowling action types, the mixed action has been recognized as the most common action used by fast bowlers (Ferdinands et al., 2010). Although the majority use the mixed action, it has an inverse effect on performance as mixed action bowlers show a lower level of accuracy compared to both front-on and side-on bowlers (Ferdinands et al., 2014; Portus, Sinclair, Burke, Moore, & Farhart, 2000). Due to the association of the mixed bowling action with bony and soft tissue injuries in the lumbar spine, numerous biomechanical studies have examined the mixed action bowling (Burnett et al., 1996; Ferdinands et al., 2014; Portus et al., 2000). Kinematic properties that relate to the bowling actions, such as stride alignment, elbow alignment, shoulder alignment, as well as counter rotation, in each of the bowling action subgroups demonstrate a range of different behaviours (Ferdinands et al., 2014). The extreme level (>30º) (Ferdinands et al., 2010) of shoulder counter rotation is a significant factor of the mixed bowling action and has repeatedly been associated with low back injuries of both junior level (Burnett et al., 1996; Elliott et al., 1992; Foster et al., 1989) and senior level fast bowlers (Portus et al., 2004). When compared to bowlers using other types of action, bowlers with mixed bowling action demonstrate hyperextension and lateral flexion (non-dominant side) of the lumbar spine at front foot contact (Burnett, Barrett, Marshall, Elliott, & Day, 1998; Zhang, Ma, & Liu, 2016). Furthermore, fast bowlers diagnosed with low back injuries demonstrate a higher range of lateral flexion of the lumbar spine (Portus et al., 2007).

High peak ground reaction force at front foot contact is another major factor associated with low back injuries in cricket fast bowlers (Bartlett et al., 1996; Worthington et al., 2013). The group of fast bowlers who previously suffered from low back stress fractures displayed a higher rate of peak force development during front foot contact (Portus et al., 2004). The bowlers with a flexed front knee at the front foot contact generate less ground reaction force compared to those with an extended front knee (Elliott, 2000). This finding was confirmed by Portus et al. (2004), who also reported knee extension during front foot contact was linked to higher peak braking force. Therefore, bowlers with an extended front knee at the front foot contact are more prone to low back injuries than front knee flexed bowlers. Greater shoulder pelvis separation angle is also a major kinematic factor that contributes to the increased risk of lumbar spinal injuries of cricket fast bowlers (Ferdinands et al., 2010; Stuelcken et al., 2010)

1.3.2. Bone health

Bone mineral density (BMD) and bone mineral content (BMC) are two main parameters to evaluate bone health (Scerpella, Buehring, Hetzel, & Heiderscheit, 2018). Dual-energy X-ray absorptiometry (DXA) is a highly accepted and widely used method to measure bone health (Li, Ford, Zhao, Balluz, & Giles, 2009). DXA scans provide information on the regional distribution of bone area, bone mineral content and bone density (Micklesfield et al., 2012). A positive relationship has been identified between bone health and physical activity which generates mechanical loading and muscle force (Frost, 2001; Micklesfield et al., 2012). It has been shown that athletes have a higher BMD than non-athletic populations (Andreoli et al., 2001; Heinonen et al., 1995). Micklesfield et al. (2012) showed that BMD at the lumbar spine and hip regions was significantly greater in cricketers compared to the physically active general public and suggested that the mechanical loading associated with cricket is beneficial for BMD. Micklesfield et al. (2012) also found a higher whole body BMD in fast bowlers compared to spin bowlers. Furthermore, Lees, Bansil, and Hind (2016) showed that BMC in the arm region and the trunk of cricket fast bowlers was significantly higher compared to the non-athletic population. In racquet sports higher bone mass and bone size has been observed in the dominant arm compared to the non-dominant arm of athletes (Haapasalo et al., 1998; Kontulainen, Sievänen, Kannus, Pasanen, & Vuori, 2003). As cricket fast bowling is a unilateral activity, there may also be differences between the dominant and non-dominant side of the body in reference to the bowling arm. Furthermore, the different bowling actions may also affect BMC and BMD of different regions of the body. To our knowledge, this has not been investigated to date and may provide useful information towards a better understanding of the potential effects of bowling action on bone health.

1.3.3. Muscle asymmetry

When considering low back muscle morphology, some studies have demonstrated spinal muscle asymmetry as a potential risk factor for low back injuries in cricket fast bowlers (Kountouris, Portus, & Cook, 2013; Ranson, Burnett, O'Sullivan, Batt, & Kerslake, 2008a). Research has identified that increasingly large quadratus lumborum (QL) musculature asymmetries are associated with an increased risk of lumbar spinal stress fractures (Crewe et al., 2013a; Engstrom, Walker, Kippers, & Mehnert, 2007a). Engstrom et al. (2007a) showed asymmetries in QL, favouring larger QL muscles on junior fast bowler's dominant side. Kountouris et al. (2013) in contrast, showed asymmetries on both the dominant and non-dominant side in junior fast bowlers with 65% showing greater proportion of asymmetries on their dominant side, while 35% showed non-dominant side asymmetries.

The above studies were conducted using MRI images of specific muscle groups. MRI scans are quite expensive, while recently DXA scans have become more affordable and easily accessible. DXA scans have been used in some recent cricket research to provide an overview of bone health, as well as body composition (Lees et al., 2016; Micklesfield et al., 2012). DXA scans can provide information on the regional distribution of fat mass and lean mass (Micklesfield et al., 2012) and may identify asymmetries between body regions (e.g. left arm versus right arm). It appears DXA scans may provide a useful screening tool for cricket fast bowlers to provide an indication of potential muscle asymmetry.

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1.4. Significance, aims and limitations

1.4.1. Aims

The primary aims of this thesis were to first identify biomechanical risk factors associated with lumbar spine injuries in cricket fast bowlers through a systematic review of the literature and secondly establish the presence of those identified risk factors among junior fast bowlers. Investigating these risk factors will provide a better understanding and more information about injury risk for lumbar spinal injuries in junior fast bowlers. These findings can then be used to inform more optimal injury prevention and injury management practices. Therefore, this thesis will consist of two studies.

- Manuscript 1 – Systematic review of the research literature
    - Aim - To conduct a systematic review of the biomechanical factors associated with lumbar spine injuries among cricket fast bowlers.

- Manuscript 2 – A pilot study into the presence of biomechanical lower back injury risk factors in junior fast bowlers.
    - Primary aim - To examine the bowling action of junior cricket fast bowlers in order to identify the presence of identified biomechanical risk factor for lower back injuries.
    - Secondary aim – To examine bone health and potential muscle asymmetries in junior cricket fast bowlers.

1.4.2. Significance

This research will provide an overall picture of biomechanical factors of cricket fast bowling and their associations with lower back injuries. Furthermore, this study will establish the presence of the identified risk factors and bowling actions among junior cricket fast bowlers. Finally, this study will explore bone health and presence of muscle asymmetries in junior fast bowlers using DXA.

1.4.3. Limitations.

It is acknowledged that the following factors may have limited the results of the present study.

1. The sample would not represent the whole population as it is restricted to junior male representative cricketers willing to participate.
2. All participants were tested in a laboratory environment and had to bowl with reflective markers attached to their body. Therefore, participants, being in an unfamiliar environment, may have changed their bowling rhythm and action.
3. Adhesiveness of the retro-reflective markers was problematic, and certain markers for some participants became unstuck, meaning some data was lost.
4. As participants were bowling at the stumps without a batsman present, they might not put their full effort into bowling.
5. As participants intentionally attempted to land their front foot on a force platform, their bowling actions may have been slightly altered.

1.4.4. Delimitations.

The below mentioned factors were delimitations of this study

1. The eligibility criteria for the participants in this study were decided by the research team and limited to junior male NSW representative cricket fast bowlers only. Hence the results of this study only reflect Australian junior elite male cricket fast bowlers' populations.

Chapter 2

Systematic Review

2. Chapter 2. Biomechanical factors associated with low back pain and lumbar spine injury in cricket fast bowlers: a systematic review

2.1. Introduction

Fast bowlers in cricket are more likely to suffer lost match time due to injury compared to all other playing positions (Ranson et al., 2013), with injury to the lumbar spine region being the most common and accounting for 40% of injuries in adult fast bowlers (Mansingh et al., 2006). Furthermore, the lumbar spine is the second most injured body region resulting in loss of match time (17%), after the thigh region (21%), and the most injured body region for no-time loss injury (16%) (Ranson et al., 2013). These findings indicate that injury to the lumbar spine region represents a significant challenge to health and availability of fast bowlers and as such, merits further investigation.

It has been shown that fast bowling exposes the lumbar spine to large loads (approximately six times body mass), in all planes of motion, including mean peak torque loads during spinal flexion, rotation and lateral flexion (Ferdinands, Kersting, & Marshall, 2009; Schaefer et al., 2018). Glazier (2010) emphasises the 'crunch factor', which is known as the instantaneous product of lateral trunk flexion and axial trunk rotational velocity of the lumbar spine (Sugaya, Morgan, Banks, Cook, & Moriya, 1997), as instrumental in the aetiology of contralateral lumbar spine injury and intervertebral disc degeneration in cricket fast bowlers. Furthermore, specific bowling actions have been identified as predisposing athletes to a lumbar spine injury.

Traditionally, three fast bowling actions are described; front-on, side-on and mixed action (Bartlett et al., 1996; Elliott et al., 1992; Worthington et al., 2013a). More recently, however, the bowling action is described using a four-category classification; front-on, semi-on, side-on, and mixed action types (Ferdinands et al., 2014; Portus et al., 2004; Ranson, Burnett, King, Patel, & O'Sullivan, 2008). Bowling actions are classified based on the shoulder and pelvis kinematics in the transverse plane during the delivery stride (Ferdinands et al., 2014), with specific reference to shoulder girdle and shoulder alignment at the back foot contact (Worthington et al., 2013a). Due to the high incidence of lumbar spine injury in cricket fast bowlers, research has been conducted into the mechanisms related to these injuries focussing particularly on the associations between injury and the fast bowling action. In early studies, the mixed bowling action was identified as increasing the risk of lumbar spine injury, due to the misalignment between the shoulder and pelvis when bowling (Bartlett et al., 1996). This bowling action was associated with higher levels of disc degeneration and a higher incidence of low back pain (Burnett et al., 1996). Extreme shoulder counter rotation is also a significant factor of the mixed bowling action and has repeatedly been associated with low back injury incidence in junior and adult bowlers (Bartlett et al., 1996; Elliott et al., 1992; Foster et al., 1989). In more recent studies, the mixed action has therefore been sub-classified based on both shoulder counter rotation, as well as shoulder alignment and pelvis shoulder separation at back foot contact (Ferdinands et al., 2014). Each sub-category in the mixed action (front-on mixed, side-on mixed, and semi-open mixed) demonstrates differences between the kinematic characteristics of the bowling action (Ferdinands et al., 2014).

This manuscript aims to systematically review the biomechanical kinematic and kinetic risk factors associated with low back pain and lumbar spine injuries in cricket fast bowlers. A better understanding of findings published to date will assist sports scientists and coaches to identify gaps in the current knowledge, in order to direct future research. Moreover, this knowledge alone can assist in identifying high-risk athletes and develop strategies targeting know risk factors.

2.2. Methodology

2.2.1. Information sources and search strategy

The electronic bibliographic databases MEDLINE, EMBASE, SCOPUS, COCHRANE LIBRARY, WEB OF SCIENCE as well as SPORTDISCUSS were used as primary search sources. The search was conducted during May 2018, using only English language and studies published within the last 26 years (1992 -2018).

The keywords used in the electronic bibliographic database searches included;

1. back pain OR back injur* OR spin* patho* ORspin* abnormal*
2. AND cricket OR fast bowl*
3. AND biomech* OR kinematic* OR kinetic*

2.2.2. Eligibility criteria

This review focussed only on experimental quantitative studies, including both cross-sectional and longitudinal studies. Please see below for the inclusion and exclusion criteria of this systematic review.

Inclusion criteria

1. Participant characteristics:
    a. Age and sex of the subjects: male or female adult (17 + y) or junior (12-16 y) male or female cricket fast bowlers.
    b. Injury definition and diagnosis method: Diagnosed with a lumbar spine injury(s) by a medical practitioner(s) OR asymptomatic with the presence of a lumbar spine abnormality on diagnostic imaging (MRI) OR no lower back injuries to the best knowledge of the participants and capable to bowl without limitation.

2. Biomechanical analysis:
    a. Studies which investigated either 3D or 2D biomechanical factors in relation to lower back injuries of cricket fast bowling only.
3. The currency of the study:
    a. Only studies conducted within the last 26 years were included in the review.

Exclusion criteria

1. Studies that investigated the effect of an intervention, such as different coaching methods or use of back braces.
2. Studies that investigated bowling action, technique and performance only without reporting injury details.
3. Studies with 3D or 2D biomechanics investigating the spin bowling action.
4. Conference papers and review papers.

2.2.3. Study selection

The first (UB) and second (XJ) reviewers conducted the review independently and selected studies based on titles and abstracts. Any discrepancies were resolved by the third reviewer (AS) to ensure consensus between reviewers. The selected articles were then reviewed based on the full-text article by both reviewers independently, with the third reviewer consulted to resolve any disagreements. When additional information/data regarding the study was required the corresponding authors of the respective studies were contacted. The reasons for the exclusion of articles were recorded.

2.2.4. Data collection process

Data were collated using a customised spreadsheet that included the participant's demographic data, methodologies, injury status, and kinematic as well as kinetic details as shown below in Table 2.1. Descriptive statistics, including mean and standard deviation, for kinetic and kinematic variables were extracted from included articles. Kinematic and kinetic factors were classified based on the type of lower back injury and bowling action classifications.

Table 2.1 Extracted information

Demographic/ Players Profile	Methodologies	Trials	Injury Status	Kinematic	Kinetic
Gender	Study design	Recorded trials.	Definition	Joints angles	GRF
Age	3D Biomechanics	Selected for analysis.	Diagnosed by whom	Alignments angles	Joint forces
Height	2D Biomechanics		Types of injuries	Angular velocity	Joint moment
Mass	Fast bowling			Approach speed	Joint power
Playing level				Stride length	Joint work
Bowling action types					

GRF – Ground reaction force

2.2.5. Methodological quality assessment

Two reviewers (UB and AX) independently performed quality and risk of bias assessments on each included article using the McMaster University Guidelines and Critical Review Form for Quantitative Studies (Law et al., 1998). This assessment tool has previously been used in systematic reviews in exercise and sports science (Pressick, Gray, Cole, & Burkett, 2016) and was chosen because all selected studies utilised quantitative methods. As shown in Table 2.3 the questions in the McMasters tool were answered as 'yes', 'no', 'not applicable (N/AP)' or 'not addressed (N/AD)'. Any discrepancies between initial answers were discussed and resolved between all three reviewers. Based on these sets of the checklist, the critical appraisal scoring system (Table 2.4) (Anaf & Sheppard, 2007) was used to allocate the numerical scoring system under the given eight sets of criteria. The methodological scores for the reviewed studies were given a score out of a maximum of 15 and were defined into three levels of quality/risk of bias according to the obtained scores, as high quality/low bias (score ≥ 10), moderate quality/moderate bias (10 > score ≥ 7) and low quality /high bias (score < 7) based on previous studies (Pressick et al., 2016).

2.3. Results

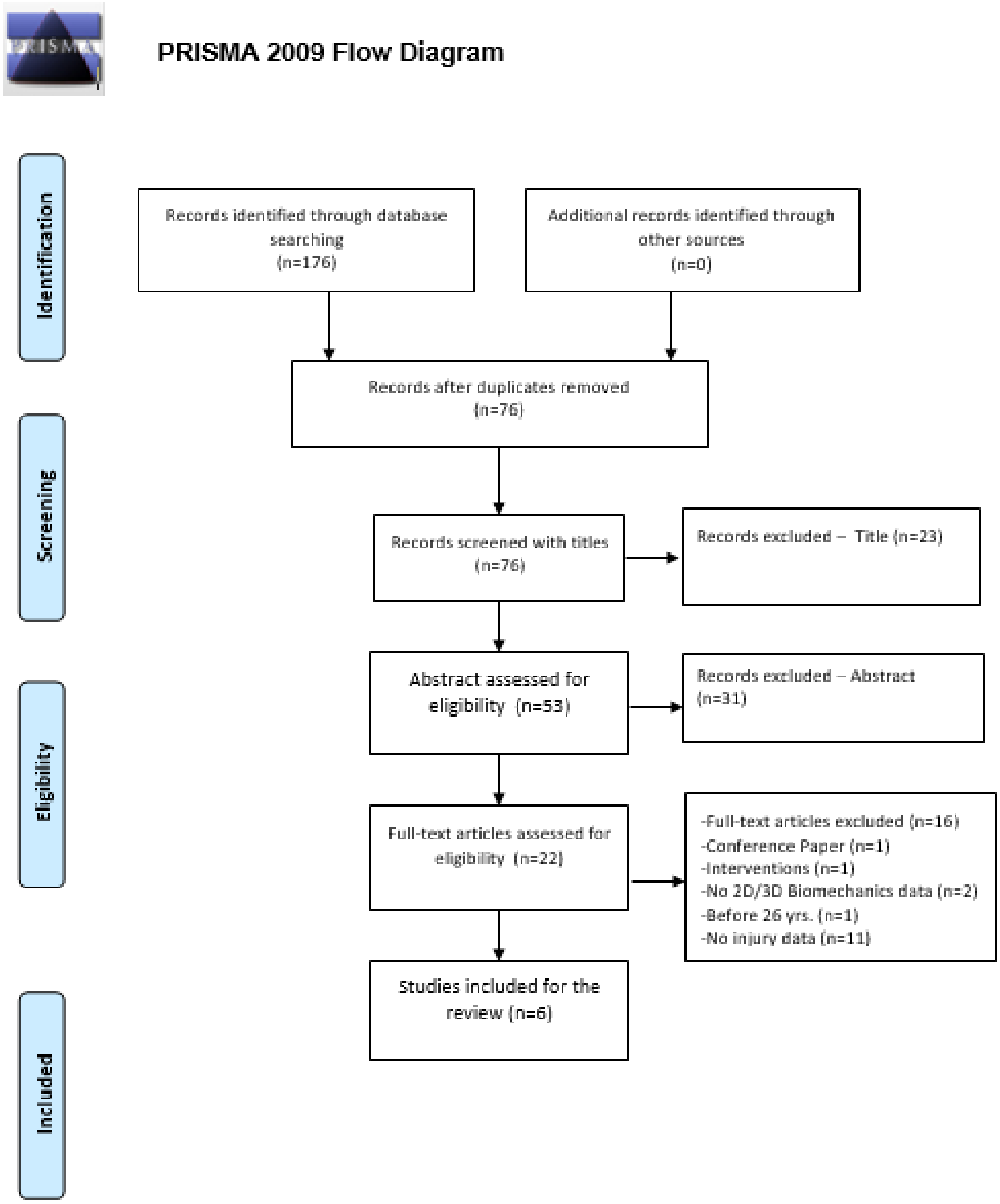
2.3.1. Study selection / Literature search

Figure 2.1 provides a summary of the literature search. A total of 176 articles were found in the electronic databases searched (Table 2.2). After excluding duplicates, 76 articles remained from searched electronic databases including, MEDLINE (14), EMBASE (14), SCOPUS (13), COCHRANE LIBRARY (4), WEB OF SCIENCE (16) and SPORTDISCUSS (15). Out of these articles, 23 were excluded after screening the title and out of the remaining 53 articles, a further 31 were excluded upon screening of the abstracts. Twenty-two full-text articles were reviewed and 16 of these were excluded due to eight different reasons, including, conference paper (1), intervention (1), no 3D/2D biomechanical data presented (2), published more than 26 years ago (1), as well as no injury data (11). These exclusions resulted in a total of six articles being included in this systematic review.

Table 2.2 Search results from each of the electronic databases

Keywords		MEDLINE	EMBASE	SCOPUS	COCHRANE LIBRARY	WEB OF SCIENCE	SPORTDISCUSS	Total
Search 1: back pain back injur* spin* patho* spin* abnormal*	OR	72919	382218	83147	17353	133254	10308	699199
Search 2 Cricket fast bowl*	OR	5922	7080	23080	884	21097	10924	68987
Search 3 biomech* kinematic* kinetic*	OR	687604	386853	831251	7222	577515	76425	25666870
Search 1&2&3	AND	33	30	39	4	38	32	176
Duplicate removed		14	14	13	4	16	15	76

Figure 2.1 Summary of the literature search



2.3.2. *Quality assessment*

Table 2.3 Results of the quality assessment of the articles included in this systematic review

Check List Studies	Bayne et al (2016)	Burnett et al. (1996)	Elliot et al (1992)	Elliot et al (1993)	Portus et al. (2004)	Stuelcken et al. (2010)
Study purpose	yes	yes	yes	yes	yes	yes
Literature	yes	yes	yes	yes	Yes	yes
Study design	Cohort	Cohort	Cohort	Cohort	Cohort	Cohort
Sample size	25	19	20	24	42	26
Sample described	yes	yes	yes	yes	yes	yes
Sample justified	N/AD	N/AD	N/AD	N/AD	N/AD	N/AD
Outcome measures reliable	N/AD	N/AD	N/AD	N/AD	N/AD	N/AD
Outcome measures valid	yes	yes	yes	yes	yes	yes
Intervention described	yes	yes	yes	yes	yes	yes
Contamination avoided	N/AP	N/AP	N/AP	N/AP	N/AP	N/AP
Co-intervention avoided	N/AP	N/AP	N/AP	N/AP	N/AP	N/AP
Statistical significance reported	yes	yes	yes	yes	yes	yes
Appropriate analysis	yes	yes	yes	yes	yes	yes
Relevance reported	yes	N/AD	N/AD	yes	N/AD	N/AD
Drop-outs reported?	yes	no	no	no	no	no
Conclusion appropriate	yes	yes	yes	yes	yes	yes

N/AP – Not Applicable; N/AD – Not Addressed

Table 2.4 Table of numerical values for the quality assessment of the articles included in this systematic review

Criteria	Max Score	Bayne et al (2016)	Burnett (1996)	Elliot et al (1992)	Elliot et al (1993)	Portus et al. (2004)	Stuelcken et al. (2010)
Study purpose	1	1	1	1	1	1	1
Literature	1	1	1	1	1	1	1
Design	1	1	1	1	1	1	1
Sample	2	1	1	1	1	1	1
Outcome	2	1	1	1	1	1	1
Intervention	3	1	1	1	1	1	1
Results	4	4	2	2	3	2	2
Conclusions	1	1	1	1	1	1	1
Total	15	11	9	9	10	9	9
Quality		High	Moderate	Moderate	High	Moderate	Moderate
Bias		Low	Moderate	Moderate	Low	Moderate	Moderate

2.3.3. *Study characteristics*

The included studies were published between 1992 and 2016. Three out of the six studies reported 3D biomechanical data (Bayne et al., 2016; Portus et al., 2004; Stuelcken et al., 2010), while the three older studies reported only 2D biomechanical data (Burnett et al., 1996; Elliott et al., 1993a; Elliott et al., 1992). All but one of the six articles included male participants only (Bayne et al., 2016; Burnett et al., 1996; Elliott et al., 1993a; Elliott et al., 1992; Portus et al., 2004), while only a single study investigated female participants (Stuelcken et al., 2010). The mean age of the study participants (n=156) ranged from 13 to 27 years. According to the quality assessment through McMaster University Guidelines and Critical Review Form for Quantitative Studies (Law et al., 1998), two out of six studies were categorised as high-quality low-bias studies while the remaining studies were categorised as moderate-quality moderate-bias studies.

2.3.4. *Statistical methodology*

All included studies conducted different types of statistical tests to analyse the data. To determine existing differences, relationships, or correlations between different variables, independent, dependent, and paired t-tests were utilised in two studies (Bayne et al., 2016; Stuelcken et al., 2010). Correlational analyses were utilised in three studies (Bayne et al., 2016; Portus et al., 2004; Stuelcken et al., 2010). To further investigate significant differences three studies utilised various post hoc tests, including the Tucky, Mann-Witney U rank test, Bonferroni and Scheffe tests (Burnett et al., 1996; Elliott et al., 1993a; Elliott et al., 1992).

2.3.5. Synthesis of results

2.3.5.1. Participant characteristics

A summary of the characteristics of the study participants is provided in Table 2.5. A total of 156 participants (n=130 males, n=26 females) with a mean age range of 13 to 27 years participated in the six studies included in the review. The playing level of the participants ranged from junior district-level up to elite international level. All the included studies were conducted in Australia. At the time of measurement of biomechanical data, all participants were deemed to be free of lumbar spine injury and low back pain. Some studies assessed eligibility of study participants via MRI scanning, in order to confirm the absence of any bone abnormalities, (Bayne et al., 2016), while others relied on assessment by a sports physician or physiotherapist to indicate the absence of back pain or injuries prior to testing (Portus et al., 2004; Stuelcken et al., 2010), or the absence of spinal abnormalities to the participant's best knowledge (Burnett et al., 1996; Elliott et al., 1993a; Elliott et al., 1992).

The prospective study design was implemented over one competitive playing season in three studies (Bayne et al., 2016; Elliott et al., 1993a; Elliott et al., 1992) and over two seasons in one study (Burnett et al., 1996). Two studies featured a retrospective study design, one was conducted over a four-year period of time (Portus et al., 2004), and one over a single competitive playing season (Stuelcken et al., 2010).

Some studies distinguished between bowling actions based on the classification of kinematic factors at either back foot initial contact, or foot flat or impact (Burnett et al., 1996; Elliott et al., 1992; Stuelcken et al., 2010). The mixed action was identified as the most common bowling action in several studies with a percentage of 49% to 78%, followed by semi-open and front-on with a percentage of 14% to 40% and 3% to 17% respectively (Burnett et al., 1996; Elliott et al., 1993a; Elliott et al., 1992; Portus et al., 2004; Stuelcken et al., 2010). The number of bowling trials investigated varied between studies. One study used four trials delivered at maximum bowling speed (Bayne et al., 2016), while trials landed on ‘good length areas’ were used by another study (Stuelcken et al., 2010). Three studies used only one bowling trial out of two maximum velocity trials (Burnett et al., 1996; Elliott et al., 1993a; Elliott et al., 1992). One study did not report details about the number of bowling trials (Portus et al., 2004). To capture the bowling action, customised full-body passive reflective marker sets ranging from 31 to 86 markers were used in all studies reporting 3D biomechanical data (Bayne et al., 2016; Portus et al., 2004; Stuelcken et al., 2010). The studies reporting 2D biomechanical data captured the bowling action from both the sagittal plane and transverse plane at 200 Hz and 100 Hz respectively (Burnett et al., 1996; Elliott et al., 1993a; Elliott et al., 1992).

Table 2.5 Characteristics of the participants and methodologies of the included studies

Reference	Participants: No.	Participants: Age/Height/ Body Mass/ Gender	Participants: Playing Level/ country	Inclusion Criteria	Study design/cohort	Bowling action	No. of trials	Marker set	Comments
Bayne et al. (2016)	25 13 non-inj. 12 inj	Non-injured: 16.0±1.2 y 180.7±5.8 cm 71.5±9.1 kg Injured: 15.5±1.4 y 175.9±9.0 cm 67.0±10.0 kg Gender: Male	Junior District / State Australia	Free of low back pain for at least 3 months preceding data collection. No appearance of acute or chronic lumbar bone stress abnormalities during MRI screening	A prospective study over one season, MRI pre- and post-season Post-season: 13 non-injured 12 injured (3 asymptomatic bone stress, 3 symptomatic bone stress, 6 not bone related back injury)	N/R	4 trials with highest ball release speed were analysed out of 18 deliveries (3 overs)	UWA full body marker set (Dempsey et al., 2007)	No significant difference between groups in age, height and body mass. Increased lateral flexion of the trunk during bowling and greater lumbar loads are associated with low back injury incidence in adolescent fast bowlers.
Burnett et al. (1996)	Season1-19 Season2-19	Season 1: 13.6 ± 0.6 y 161 ± 11.1 cm 51.2 ±7.5 kg Season 2: 16.3 ± 0.6 y 180 ± 7.1 cm 68.4 ± 10 Gender: Male	School/ Club Australia	No spinal abnormalities to the bowlers' knowledge at the start of the testing	A prospective study over two seasons and MRI follow up study. Season 1 Back pain and disk degeneration – n=4 Season 2 Back pain and disk degeneration – n=11	Season 1: 78% mixed (n=15) 11% side on (n=2) 11% front on (n=2) Season 2: 63% mixed (n=12) 26% side on (n=5) 11% front on (n=2)	One from the two maximum velocity trials	N/ A, filmed in the sagittal plane at 200Hz and transverse plane at 100Hz.	The progression of disc degeneration was found to be related to those bowlers who used mixed bowling action
Elliot et al. 1992	20	17.9 y Gender: Male	State Australia	No spinal abnormalities to the bowlers' knowledge at the start of the testing	A prospective study over one season, CT and MRI scan at the beginning. No abnormal radiologic features- n= 3 Disc degeneration or bulging – n=6 Spondylolysis, Spondylolisthesis, pedicle sclerosis – n= 11	80% mixed (n=16) 20% side on (n=4)	One from the two maximum velocity trials	N/ A, filmed in the sagittal plane at 200Hz and transverse plane at 100Hz.	Bowlers who used mixed bowling action more likely to present radiological abnormalities. Bowlers who have higher ball release height relative to their standing height more likely to present bony abnormalities.
Elliot et al. 1993	24	13.7 ± 0.5 y 158 ± 0.1 cm 51 ± 6.8 kg Gender: Male	School/ Club Australia	No spinal abnormalities to the bowlers' knowledge at the start of the testing	A prospective study over one season, MRI scans at the beginning. Normal radiological features- n = 19 Abnormal radiological features- n = 5	62.5% mixed (n=15) 16.7% side on (n=4) 20.8% front on (n=7)	One from the two maximum velocity trials	N/ A, filmed in the sagittal plane at 200Hz and transverse plane at 100Hz.	Higher shoulder counter rotation is displayed by fast bowlers with disk abnormalities.
Portus et al. (2004)	42	22.4 ± 3.5 Gender: Male	High-performance fast bowlers	History of injuries suffered by bowlers was assessed by sports physicians	A longitudinal retrospective study over the four year period of time. Trunk injury history - n=30 Trunk injury reported - n=27 Stress fractures of the lumbar spine pars interarticularis – n=9 Back sprain, Injury to disc, facet joint or ligaments – n=11 Muscle side strain – n=7 No trunk injury – n= 5	74% mixed (n=31) 5% side on (n=2) 7% front on (n=3) 14% semi-open (n=6)	N/R	N/R	Shoulder counter rotation is significantly higher in bowlers who reported lumbar spine stress fractures. Bowlers suffering lower back injuries exhibited the typical characteristic of mixed bowling action.
Stuelcken et al. (2010)	26	22.5 ± 4.5 y 171.5 ± 5 cm 66.2 ± 7.5 kg Gender: Female	Elite Female	No reported back pain or injuries at the start of the testing with the assessed by sports physicians.	Retrospective study over the season. History of LBP – n=14	73% mixed (n=19) 4% side-on (n=1) 0% front on 23% semi-open (n=6)	4 from 25 with high accuracy target by landing good length	48 marker (Plug-in – Gait Market set) (Salter, Sinclair, & Portus, 2007)	Female fast bowlers who have higher shoulder counter rotations no more likely to have a history of low back pain than others. Bowlers with LBP positioned the thorax in more left lateral flexion relative to the pelvis.

CT – Computed tomography; Inj.: Injured; LBP: Low back pain; MRI: Magnetic resonance imaging; N/A: Not applicable; N/R: Not reported, UWA: University of western Australia, y: Years

2.3.5.2. Kinetic risk factors of fast bowling associated with low back injuries.

The peak lumbar lateral flexion power of injured junior male fast bowlers (25.8 ± 16.2 Nm kg^{-1} m^{-1}) was significantly higher than that of non-injured fast bowlers (14.4 ± 7.7 Nm kg^{-1} m^{-1}) (t=2.292, p=0.043) (Bayne et al., 2016). Furthermore, significant differences in joint moments between injured and non-injured fast bowlers were also found. Injured junior male fast bowlers (10.5 ± 4.9 / 12.5 ± 2.6 Nm kg^{-1} m^{-1}) had significantly higher joint moment in both peak lumbar flexion (t =2.29, p = 0.04) and peak lumbar lateral flexion (t = 2.08, p= 0.05), than non-injured fast bowlers (6.9 ± 2.5 / 10.6 ± 1.9 Nm kg^{-1} m^{-1}) (Bayne et al., 2016).

Apart from the above-mentioned kinetic factors that were significantly different between injured and non-injured fast bowlers, some articles reported an association between Ground Reaction Force (GRF) and ball release speed. According to Portus et al. (2004), the peak posterior GRF at Front Foot Contact (FFC) was moderately and positively correlated with ball release speed (r=0.43, p<0.01) for both injured and non-injured athletes. In contrast, several studies reported no significant relationship between peak posterior GRF at FFC and kinetic/kinematic variables (Bayne et al., 2016; Elliott et al., 1993a; Elliott et al., 1992). Similarly, these studies reported no significant differences between injured and non-injured groups in posterior GRF. Moreover, Portus et al. (2004) found a large negative correlation of time (s) to peak vertical GRF during FFC with ball release speed (r = -0.65, p < 0.001) and a moderate negative correlation of time (s) to peak posterior GRF during FFC with ball release speed (r= -0.32, p < 0.01) in non-injured as well as injured groups. A summary of the kinetic factors is presented in Table 2.6.

Table 2.6 Main findings for kinetic factors in non-injured fast bowlers and fast bowlers with a current lumbar spine injury and/or abnormality

Description	All	Injured	No-Injury/ Control	Main findings	Reference
Kinetic factors					
Joint power (W kg^{-1} m^{-1})					
Peak lumbar LF power		25.8 ± 16.2	14.4 ± 7.7	Injured had higher peak lateral flexion power than non-injured (t=2.203, p=0.43)	Bayne et al. (2016)
Joint moment (Nm kg^{-1} m^{-1})					
Peak lumbar flexion		10.5 ± 4.9	6.9 ± 2.5	Injured had higher peak lumbar flexion moment than non-injured (t = 2.292, p = 0.036)	Bayne et al. (2016)
Peak lumbar lateral flexion		12.5 ± 2.6	10.6 ± 1.9	Injured had higher peak lumbar lateral flexion moment than non-injured (t = 2.079, p = 0.049)	Bayne et al. (2016)
Ground reaction force					
F_{POST} at FFC (BW)	4.5 ± 1			Moderate positive correlation with ball release speed (r=0.43, p < 0.01)	Portus et al. (2004)
F_{POST} during FFC (BM)		3.4 ± 0.5	3.3 ± 0.7	No significant differences /correlation	Bayne et al. (2016)
F_{POST} at FFC (BM)		5.2 ± 0.9	4.8 ± 1.4	No significant differences /correlation	Elliot et al (1993)
F_{POST} at FFC (BM)	1.9 ± 1	Stress fractures - 2 ± 0 Back Strain - 2 ± 0	1.9	No significant differences /correlation	Elliot et al (1992)
Time to F_V during FFC (s)		Stress fractures - 0.06 ± 0.04 Back Strain - 0.08 ± 0.02 Side Strain - 0.08 ± 0.02	0.09 ± 0.01	Large negative correlation with ball release speed (r= -0.65, p < 0.01)	Portus et al. (2004)
Time to F_{POST} during FFC (s)		Stress fractures - 0.07 ± 0.03 Back Strain - 0.08 ± 0.02 Side Strain - 0.08 ± 0.02	0.11 ± 0.06	Moderate negative correlation with ball release speed (r= -0.32, p < 0.01)	Portus et al. (2004)

Body Mass (BM), Front-foot contact (FFC), Lateral flexion (LF), Peak vertical ground reaction force (F_V), Peak posterior ground reaction force (F_{POST})

2.3.5.3. Kinematic risk factors of fast bowling associated with low back injuries.

A summary of the kinematic factors is presented in Table 2.7. When considering joint angles during the delivery stride, Bayne et al. (2016) found that non-injured junior male fast bowlers displayed significantly larger hip flexion at FFC compared to injured junior male fast bowlers ($t=2.076$, $p=0.049$). However, in contrast to these findings, Portus et al. (2004) found no significant difference in hip flexion angle between non-injured and in fast bowlers with an injury history of stress fractures, back strain or side strain. Furthermore, in respect to joint angle, knee extension range during FFC (10º ± 9), as well as knee angle (150º ± 20) at ball release, showed moderate positive correlations with peak braking impact force ($r=0.33$, $p<0.05$ / $r= 0.38$, $p<0.05$) regardless of injury status of the fast bowlers (Portus et al., 2004). Similarly, knee angle at ball release displayed a moderate positive correlation with peak vertical impact force ($r= 0.31$, $p<0.05$), while knee extension range during FFC displayed a moderate positive correlation with ball release speed ($r=0.37$, $p=0.02$) (Portus et al., 2004). However, no significant differences or correlations between injury status and knee angle were found in the study conducted by Elliott et al. (1993a).

For findings related to segment alignments, the alignment of the shoulders (on the transverse plane towards to anticlockwise from the direction of bowling), as well as minimum shoulder alignment, in non-injured fast bowlers were found to be significantly lower compared to injured fast bowlers (Elliott et al., 1992). In contrast, Elliott et al. (1993a) reported no significant differences for shoulder segment alignment between injured and non-injured fast bowlers. Although these two studies reported contrasting findings, comparisons between these studies are difficult given the age and the playing level of the study participants in each of the studies. In Elliott et al. (1993a) study participants were aged 13.5 ± 0.7 years and were state-level players, while the participants in Elliott et al. (1992) were aged 17.9 ± 1.6 years and played school and club-level cricket.

When considering body segment angles, a significant difference was found in thorax lateral flexion between injured fast bowlers and non-injured fast bowlers at both FFC and ball release (Bayne et al., 2016; Stuelcken et al., 2010). The injured group displayed significantly greater lateral flexion (19.9 ± 6 / 49.8 ± 5.9) away from the bowling arm compared to the non-injured group (15 ± 5.1 / 40.2 ± 7.8) at both FFC (p=0.04) and ball release (, p=0.002) (Bayne et al., 2016). Similar results were shown in a study conducted on female fast bowlers with injured female fast bowlers displaying a significantly greater range of thorax lateral flexion compared to non-injured female fast bowlers (p = 0.004, d = 1.25) (Stuelcken et al., 2010). Moreover, Bayne et al. (2016) identified significant differences in pelvis rotation toward the non-dominant side at ball release between injured and non-injured fast bowlers (t=2.408, p=0.024).

According to Portus et al. (2004), shoulder counter rotation was significantly higher in fast bowlers with stress fractures than in non-injured fast bowlers (p=0.01). However, a recent study by Bayne et al. (2016), did not highlight any significant differences in shoulder counter rotation between injured and non-injured fast bowlers.

Table 2.7 Main findings for kinematic factors in non-injured fast bowlers and fast bowlers with a current lumbar spine injury and/or abnormality.

Description	Reference	All	Injured	No-Injury/ Control	D.Degen	Spon*, PS	Stress Fracture	Back Strain	Side Strain	Comments
Joint Angles (°)										
Knee extension range during FFC	Portus et al. (2004)	10± 9								Moderate positive correlation with peak braking impact force (r= 0.33, p<0.05) and ball release speed (r=0.37, p=0.02)
Knee angle at BR	Portus et al. (2004)	150± 20								Moderate positive correlation with peak vertical impact force (r= 0.31, p<0.05) and peak braking impact force (r=0.38, p<0.05) during FFC
Knee angle at BR	Ellior et al (1993)		153.2± 23.6	152.6± 23.8						
Hip flexion angle at FFC	Portus et al. (2004)			121± 16			130± 12	125± 14	125± 9	
Hip flexion angle at FFC	Bayne et al. (2016)		46.1± 5.6	50.7± 5.5						The non-injured group displayed significantly larger hip flexion at FFC compared to injured group (t=2.076, p=0.049)
Segment Alignment (°)										
Alignment of the shoulders BFC	Elliott et al (1992)	206.3± 32			179	206	197			Non-injured group (No-bone abnormity) displayed significantly lower shoulder alignment compared to bone abnormality groups.
Alignment of the shoulders BFC	Elliott et al (1993)		218.6± 14.4	121.9± 12.2						
Minimum Shoulder alignment at BR	Elliott et al (1992)	187.4 ± 13			179	181	193			Non-injured group (No-bone abnormity) displayed significantly lower minimum shoulder alignment compared bone abnormality group
Minimum Shoulder alignment at BR	Elliott et al (1993)		188.6± 8.1	194.0± 10.1						
Segment Angles (°)										
Thorax lateral flexion at FFC	Bayne et al. (2016)		19.9± 6	15± 5.1						The injured group displayed significantly greater lateral flexion away from the bowling arm at FFC compared to non-injured group (t=2.187, p=0.039)
Thorax lateral flexion at BR	Bayne et al. (2016)		49.8± 5.9	40.2± 7.8						The injured group displayed significantly greater lateral flexion away from the bowling arm at BR compared to non-injured group (t=3.396, p=0.002)
The range of thorax lateral flexion	Stuelcken et al. (2010)		48.6± 5.7	42± 4.7						The injured group displayed a significantly greater range of thorax lateral flexion compared to the non-injured group. (p=0.004, d=1.25)
Pelvis rotation at BR	Bayne et al. (2016)		287.3± 10.8	276.6± 11.4						The injured group displayed significantly greater pelvis rotation at BR compared to non-injured group (t=2.408, p=0.024)
Counter-Rotation (°)										
Shoulder counter-rotation	Portus et al. (2004)			19± 10			41± 10	36± 15	27± 13	Shoulder counter-rotation significantly higher in stress fracture group than non-injured group (p=0.01)
Shoulder counter-rotation	Elliott et al (1993)		30± 10.5	18.9± 9.3						Shoulder counter-rotation significantly higher in the injured group than injured (disc abnormality) group (p=0.08)
Shoulder counter-rotation	Bayne et al. (2016)		35.7± 12.3	32.5± 11.8						

Back foot contact (BFC),Ball release (BR), Disk degeneration or bulging (D.Degen/Bul*), Front-foot contact (FFC), Spondylolysis, Spondylolisthesis, Pedicle sclerosis (Spon*,PS)

2.4. Discussion

The aim of this systematic review was to provide a better understanding of the biomechanical factors that are associated with lower back injury in cricket fast bowlers. Available information regarding fast bowling kinetics and kinematics differentiating between fast bowlers with and without current low back injury and/or abnormality were synthesised . Many interesting studies have been conducted in the area of cricket fast bowling and low back injuries. These studies have reported valuable findings regarding both kinematic and kinetic factors of cricket fast bowling and their relationship to low back injuries.

Three of the studies out of six included in this review utilised 3D biomechanical analyses (Bayne et al., 2016; Portus et al., 2004; Stuelcken et al., 2010), while the three older studies utilised 2D biomechanical analyses (Burnett et al., 1996; Elliott et al., 1993a; Elliott et al., 1992). However, out of these six included studies only four studies used force plates to report cricket fast bowling kinetics (Bayne et al., 2016; Elliott et al., 1993a; Elliott et al., 1992; Portus et al., 2004).

None of the studies reported any significant differences in ground reaction forces between injured and non-injured fast bowlers. However, the study conducted by Portus et al. (2004), reported a moderate positive correlation of posterior GRF with ball release speed, while the other three studies found no significant correlations. High GRF may convert into the kinetic energy and assist to generate the ball release speed, hence a positive correlation is possible. Moreover, Portus et al. (2004) reported a large negative correlation ($r = -0.65$) and moderate negative correlation ($r = -0.32$) of time to peak GRF vertical and posterior respectively with ball release speed. These findings suggest less time to generate the peak ground reaction force may help to convert GRF to kinetic energy more rapidly and generate ball speed. Overall this finding indicates that GRF contributes to performance and not necessarily to the development of injuries in cricket fast bowlers when taken in isolation without considering kinematics.

Although no other studies reported any significant findings for GRF, the findings reported by Portus et al. (2004) featured a large sample of high-performance participants (n=42), which highlights the practical significance of this study. All the studies to date have focused on front foot contact GRF and none of the studies has investigated back foot contact GRF. Therefore, to build on the limited research on GRFs of cricket fast bowlers to date, further research is recommended, in particular with a focus on rear foot contact GRF.

Lumbar joint moments were highlighted as one of the major kinetic factors that differ between injured and non-injured fast bowlers. In a recent study, Bayne et al. (2016) pointed out that the injured fast bowlers displayed a higher moment in both lumbar flexion and lumbar lateral flexion compared to non-injured fast bowlers (refer to Table 2.6). This finding, however, was only reported for a single study, which featured junior male fast bowlers. Furthermore, the same study also found that peak lumbar lateral flexion power was higher in injured fast bowlers than in non-injured fast bowlers (Bayne et al., 2016). Although only one study pointed out these factors, this study was identified as a high-quality study according to McMaster University Guidelines and Critical Review Form for Quantitative Studies (Law et al., 1998). In senior male and female fast bowlers, no significant differences in kinetic variables were found between injured and non-injured fast bowlers (Portus et al., 2004; Stuelcken et al., 2010). This is may be due to an adaptation over time. Although kinematic cricket fast bowling data are routinely reported, only limited kinetic data, primarily focused on front foot kinetics during fast bowling, have been reported (Bayne et al., 2016; Elliott et al., 1993a; Elliott et al., 1992; Portus et al., 2004). Hence, further research inclusive of monitoring of both kinematic and kinetic data is recommended, in order to better understand the potential differences between injured and non-injured fast bowlers of both sexes competing at different levels, in both senior and junior age groups.

When considering kinematic factors, several segment angles were reported to differ between fast bowlers with and without current low back injury and/or abnormality. For knee joint angles, no studies have reported any significant differences and/or correlations between injured and non-injured athletes. However, it has been suggested that having a flexed knee at front foot initial contact and an extended knee before ball release, may reduce impact forces and enable increased ball release speed, respectively (Bartlett et al., 1996). Moreover, a moderate positive correlation has been reported between knee extension range ($10^{o} \pm 5$) during FFC and ball release speed, as well as peak impact force (Portus et al., 2004). These findings suggest that bowlers who have an extended or extending knee at FFC are able to generate higher ball release and impact force. The same study also reported a moderate positive correlation of knee angle with peak vertical and braking impact force. This may be due to the efficient transfer of kinetic energy through the extended or extending knee at FFC, to the ball, which may help to generate higher ball release speed. Even though there were no differences in knee joint angles reported between injured and non-injured fast bowlers, the practical implications of the knee joint angles for ball release speed and impact forces are important to consider.

A significant difference in hip flexion angle at FFC between injured and non-injured fast bowlers was identified by Bayne et al. (2016) in junior district/state fast bowlers (n=25). In this study, the 12 junior fast bowlers who suffered a low back injury demonstrated a lower hip flexion angle (Table 2.7) at FFC than the non-injured athletes. However, Portus et al. (2004) did not find any significant differences in hip flexion angle between injured and non-injured senior high-performance fast bowlers (n=45). It has been suggested that anatomical differences between the younger and older spine may place younger fast bowlers at higher risk of back injuries (Johnson et al., 2012). It is important to focus future investigations on younger fast bowlers and implement strategies to reduce their injury risk potentially through correction of bowling technique in these young athletes.

In two studies thorax lateral flexion was identified as a kinematic factor that differs between injured and non-injured fast bowlers of both sexes (Bayne et al., 2016; Stuelcken et al., 2010). Bayne et al. (2016) found an approximately 10-degree higher thorax lateral flexion (towards the non-dominant side) at ball release in injured male junior fast bowlers than in non-injured bowlers. Elite female bowlers with a history of low back pain showed a larger range of lateral flexion of the thorax relative to the pelvis during the delivery stride than female bowlers without a history of low back pain (Stuelcken et al., 2010). It appears that in both junior male and senior female fast bowlers screening for lateral flexion of the spine during fast bowling may be a useful injury prevention tool to assist in the correction of technique.

Another kinematic factor that showed differences between injured and non-injured fast bowlers is pelvis rotation. Male junior fast bowlers with a low back injury showed approximately 10 degrees greater pelvis rotation (towards the non-dominant side) at ball release than non-injured fast bowlers (Bayne et al., 2016). None of the other included studies, however, reported a difference in pelvis rotation between groups. Bayne et al. (2016) suggest that the greater pelvis rotation combined with increased thorax lateral flexion in injured fast bowlers may generate large torsional stress on the lumbar spine. Therefore, they recommend a training program focussing on dynamic control of the lumbo-pelvic-hip complex in junior fast bowlers to achieve better technique.

A significantly higher shoulder counter rotation was identified in injured fast bowlers compared to non-injured fast bowlers for both junior and elite senior players (Elliott et al., 1993a; Portus et al., 2004). A review on back injuries and fast bowling published in 2000 suggests that during the delivery stride fast bowlers should minimise counter-rotation of the shoulders (Elliott, 2000). However, these findings on shoulder counter rotation were limited to only a small number of studies. Moreover, the study conducted in female fast bowlers (Stuelcken et al., 2010) identified large positive correlations between the alignment of the shoulders at BFC and shoulder counter rotation and no difference in shoulder counter-rotation between the groups with and without a history of low back pain. Due to the conflicting findings of the limited number of studies on shoulder counter rotation in cricket fast bowlers further research on shoulder kinematics is recommended to clarify the association between shoulder kinematics and injury incidents of cricket fast bowlers.

2.5. Conclusion

A number of cricket fast bowling biomechanical factors associated with low back injuries/pain were identified through this systematic review. Both kinetic variables, such as lumbar lateral flexion power, lateral flexion moment, and kinematic variables, such as higher hip flexion angle, higher shoulder alignment, higher thorax lateral flexion, higher pelvis rotation, as well as higher shoulder counter rotation, were found to be associated with risk of injury occurrence. However, a number of conflicting findings were reported. Furthermore, comparisons between studies are confounded due to the differences in study participant age, gender and playing level, as well as differences in study methodologies used such as 3D and 2D biomechanical data collections, using of different marker sets. Further research is needed to investigate the validity such as threshold levels of the identified biomechanical risk factors, and the association between cricket fast bowling technique and risk of lumbar spine injury, particularly in youth participants, who are still growing and consequently physically vulnerable spines compared to adults.

Chapter 3

Experimental Study

3. Chapter 3. A pilot study investigating biomechanical characteristics, bone health and muscle distribution in junior cricket fast bowlers

3.1. Introduction

Non-symmetrical movement patterns during cricket fast bowling play a large role in the development of lower back injuries (Ferdinands et al., 2010; Ferdinands et al., 2010a). The injury prevalence for the cricket fast bowlers is approximately 15% and the most prevalent injury among fast bowlers is non-dominant side lumbar stress fracture (Orchard et al., 2006). In an attempt to achieve maximum ball delivery speed, the trunk is hyperextended, laterally flexed and rotated during fast bowling, which produces significant loading of the lumbar spine (Bartlett et al., 1996; Burnett et al., 1998). It is therefore not surprising that there is a high incidence of lower back injuries in cricket fast bowlers.

As discussed in the systematic review in Chapter 2, various kinetic and kinematic factors of the cricket fast bowling action have been identified as risk factors for lower back injuries among fast bowlers of different playing levels and ages. A review by Bartlett et al. (1996) showed that greater ground reaction force at front foot contact was one of the prime contributors to lower back injuries in cricket fast bowlers (Bartlett et al., 1996). The magnitude of ground reaction forces at front-foot contact range from 3.8 to 9.0 times body mass (BM) for peak vertical ground reaction forces and from 1.4 to 4.5 times BW for peak braking ground reaction forces (Bartlett et al., 1996; Hurrion, Dyson, & Hale, 2000). Moreover, bowlers with previous lower back stress fractures demonstrate a non-significant trend towards a faster rate of peak vertical and peak breaking ground reaction force development at the front foot contact phase, compared to non-injured bowlers (Portus et al., 2004).

Front leg kinematics during the front foot-contact phase of a bowling delivery may also contribute to the development of lower back injuries in fast bowlers (Foster et al., 1989; Portus et al., 2004; Worthington et al., 2013). Portus et al. (2004) found that bowlers who demonstrated greater front leg knee extension ($10^{\circ} \pm 9$) during front foot contact were more prone to back injuries. Though front foot kinematics appear not to be related to injury risk, some studies have reported an association between increased injury risk, knee extension angles and other kinematic and kinetic factors of fast bowling. Portus et al. (2004) showed that fast bowlers who demonstrated an extended knee at FFC had higher bowling delivery speed compared to bowlers with a flexed knee at FFC. Similarly, front knee flexion angles appear to be correlated with both lumbar spine rotation angles and as lateral bending moments (Ferdinands et al., 2010a). Hence, it appears that front knee angles may significantly impact on lumbar spine loading. As such, front leg kinematics should be the focus of further investigations.

In addition to front foot kinetics and kinematics, shoulder counter rotation has also been identified as potentially leading to increased risk of lower back injury. Fast bowlers with previous lumbar spine stress fractures have demonstrated significantly greater shoulder counter rotation (mean $41^{\circ}\pm11$) compared to non-injured fast bowlers (Portus et al., 2004). Furthermore, Crewe, Campbell, Elliott, and Alderson (2013) reported that fast bowlers with greater shoulder counter rotation (mean 35.1°) demonstrated increased lumbo-pelvic loading (greater peak rotational moment and shear forces in the transverse plane and anterior-posterior plane, respectively). Fast bowlers are categorised as mixed action bowlers if they demonstrate shoulder counter rotation greater than 30° (Elliott, 2000; Portus et al., 2004), hence mixed action bowlers appear to be at greater risk of lumbar spine injuries.

In addition to the above-mentioned factors, greater pelvic–shoulder separation angle at rear foot contact has been associated with an increased risk of soft tissue injuries (back muscle sprain) (Portus et al., 2004). This may be due to the rapid re-alignment of the shoulder and pelvis segment during BFC to FFC generating great rotational forces, resulting in increased torsion stress to the lumbar region. Moreover, bowlers displaying greater lateral flexion (49.8º ± 5.9) (to the non-dominant side) of the lumbar spine during the delivery stride may also be at an increased risk of lumbar injuries (Bayne et al., 2016), which may be due to rapid loading of the lumbar facet joints when in this position. Ferdinands et al. (2010a) point out that in order to identify the causal mechanism of lumbar spinal injuries, not only kinematic but also kinetic measures are necessary in order to adequately assess the magnitude of spinal loading. Hence, further research investigating the association between fast bowling kinematic and kinetic variables and the potential negative impact on the lumbar spine region is merited.

According to the systematic review conducted in Chapter Two, higher peak lumbar lateral flexion power and higher peak lumbar lateral flexion moment, as well as higher peak lumbar flexion moment, were identified as main kinetic factors that are associated with lower back injuries in cricket fast bowlers (Bayne et al., 2016). Lower hip flexion angles (Bayne et al., 2016), increased shoulder alignment (Elliott et al., 1992), larger lateral flexion of the thoracic segment, as well as higher pelvis rotation (Bayne et al., 2016; Stuelcken et al., 2010) and higher shoulder counter rotation (Elliott et al., 1992; Portus et al., 2004; Stuelcken et al., 2010) were the identified key kinematic factors that were associated with lower back injuries of cricket fast bowlers (see Chapter Two).

Although various risk factors for lower back injuries have been associated with the cricket fast bowling action, only limited data have been reported investigating the association between bowling action and bone mineral density in cricket fast bowlers. It is hypothesised that the high spinal loads associated with fast bowling may affect the bone mineral density of the spine due to the repetitive high impact nature of the fast bowling technique (Scerpella et al., 2018). Early efforts to investigate this association has shown that bone mineral density of the lumbar spine and the hip was significantly greater in cricketers compared to other physically active people (Micklesfield et al., 2012). Furthermore, the same study reported that fast bowlers possess greater lean mass and bone mineral content in the trunk area compared to non-athletic populations. Fast bowlers also demonstrate significantly greater unilateral differences in bone mineral content in the arm region compared to the non-athletic control group (Lees et al., 2016). Furthermore, the fast bowling action is likely to result in muscle asymmetries between the dominant and non-dominant side of the body (Kountouris, Portus, & Cook, 2012). The nature of the aforementioned associations in developing younger-aged cricket fast bowlers remains unknown. Dual-energy X-ray absorptiometry (DXA) scans measure both bone mineral density and lean muscle mass distribution and can therefore be used to characterise adaptations resulting from repeated fast bowling. Several studies have shown that DXA scans provide a valid and reliable measure of body composition (Nana, Slater, Stewart, & Burke, 2015; Rosenfalck, Almdal, Gotfredsen, Højgaard, & Hilsted, 1995; Roubenoff, Kehayias, Dawson-Hughes, & Heymsfield, 1993). Hence, this type of scanning may have the potential to assist as a screening tool in cricket fast bowlers.

Adolescent cricket fast bowlers (10-19 years in age) are a special grouping of athletes who are at increased risk of lower back injuries (Bayne et al., 2016). This increased risk is because they are in a critical period of physical growth and musculoskeletal maturation (Logsdon, 2007; Schaefer et al., 2018). To date, however, there remains a paucity of research investigating the kinematics and kinetics of cricket fast bowling actions, and the presence of known risk factors, in this population. The current study therefore characterised the prevalence of known biomechanical risk factors, as identified in the systematic review, for lower back injuries in male junior fast bowlers. Furthermore, participants dominant and non-dominant side BMD and LM DXA scans findings were compared, and charactered based on bowling actions (mixed and semi-open).

3.2. Methodology

3.2.1. Participants

Eleven male junior state and/or district representative cricket fast bowlers (mean age 13.8 ± 0.6y, mean height 173.9 ± 5.3cm, mean mass 63.5 ± 5.7kg) from the Newcastle and Central Coast regions of Australia volunteered to participate in this study. Nine participants were right-handed, and two participants were left-handed. Data of the left-handed bowlers were converted on to right-handed and all reported as the dominant or non-dominant arm and leg. At the time of the testing, all the participants were free of injuries and low back pain. All participants underwent a pre-screen and injury history questionnaire (Appendix 3.1) followed by a physiotherapist-led assessment, which included a range of motion assessment (lumbar spine and hip) and pain provocation tests (Appendix 3.2). This assessment was done to ensure that participants were not injured and were able to participate without restriction in all experimental tasks. The athletes and their parents were given the opportunity to have any questions answered by the researchers. As all participants were under 18, written informed consent (Appendix 3.3) was obtained prior to the testing from each participant, as well as from a parent or guardian. All procedures in this study were approved by the University's Human Ethics Committee (H-2015-0059) (Appendix 3.4).

3.2.2. Experimental protocol

All participants attended data collection sessions during the cricket pre-season period, according to the sequence illustrated below in Figure 3.1. The data collection protocol comprised of a series of questionnaires, including a coronary artery disease risk factor stratification questionnaire (Appendix 3.5) and injury history questionnaire (Appendix 3.1), followed by an assessment by a physiotherapist to ensure the participant's readiness to complete the experimental task. Once participants were cleared to participate they underwent a whole body DXA scan followed by a biomechanical assessment of fast bowling technique.

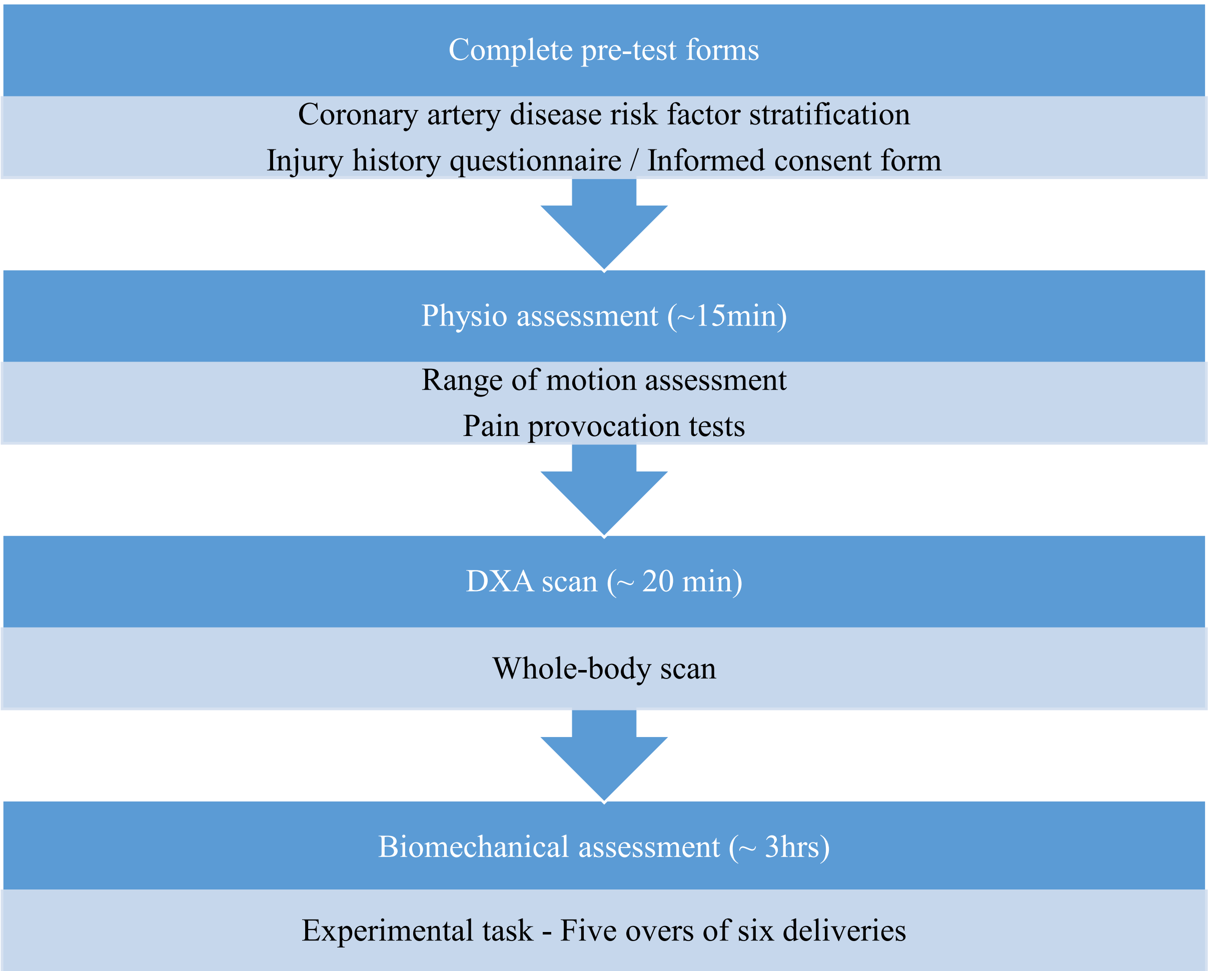


Figure 3.1 Data collection sequence

3.2.3. DXA scans

All participants underwent a whole-body dual-energy X-ray absorptiometry (DXA) scan (Hologic Discovery QDR Series, Marlborough, MA, USA) prior to the experimental bowling task. The participants were positioned in the middle of the scanner bed with their hands facing their thighs and their legs/feet turned inwards at the hips. The participants were instructed to stay as still as possible during the seven minutes of scanning, while the scanner arm overhead and the DXA bed were moving to perform the scan. Daily quality control scans were performed before each test.

Each DXA scan measures bone area (cm^2) and bone mineral content (g) of the left and right arm, leg and ribs, as well as thoracic and lumbar spine and pelvis. Bone mineral density (g/cm^2) for each of these regions is calculated by dividing BMC by bone area. The age range of the participants and the resulting differences in maturation status are likely to have affected bone area. To account for this effect of maturation only bone mineral density will be reported on. The other DXA variable of interest is lean muscle mass (g), which is reported for the left and right arm and leg, as well as the trunk.

3.2.4. Biomechanical assessment

Biomechanical testing of the fast bowling action was conducted in the biomechanics laboratory of the University of Newcastle Central Coast Campus. The height, body mass, as well as trunk anthropometry measurements (hip depth, xyphoid depth, chest depth) of each participant were recorded, with resulting measurements entered into anatomical modelling reference equations. Seventy-two passive reflective markers were then attached to anatomical landmarks on the participant's upper and lower extremities, pelvis, torso and head, according to the guidelines by Schaefer et al. (2018). A detailed overview of the marker set is provided in Appendix 3.6). Markers were placed on the participant's shoes at the first and fifth metatarsal head, mid-anterior foot, and lateral aspect of calcaneus in order to mark anatomical landmarks on the foot.

Markers were attached to the body including lateral and medial malleolus, lateral and medial femoral epicondyle, lateral shank, anterior distal and proximal shank, greater trochanter, lateral thigh, anterior distal and proximal thigh, in order to mark anatomical landmarks of the pelvis and lower limb. More markers were attached on anterior and posterior superior iliac crest, xiphoid process, sternal notch, lumbo-sacral (L5-S1) intervertebral joint space, thoraco-lumbar (T12-L1) intervertebral joint space, the ribcage bilaterally at the level of the T12-L1 intervertebral joint space and immediately superior to the iliac crest marker, five lumbar segment tracking markers, first thoracic vertebra (T1), acromion, the anterior and posterior aspect of the shoulder, lateral and medial epicondyle of the elbow, radial and ulnar styloid, dorsal aspect of the hand, forehead and left and right tragus in order to mark anatomical land marks of the torso, upper limbs and the head (Appendix 3.6) . The cricket ball used during the experimental task was marked with three markers in order to allow for the measurement of bowling speed. Participants then performed a single static trial, during which they were instructed to stand still in the anatomical position while standing astride on two adjacently located multichannel force plates (2,000 Hz, Kistler, Winterthur, Switzerland). The force plates featured built-in charge amplifiers (Type 9281CA and 9281 EA, Kistler, Winterthur, Switzerland) and were connected to a control unit (Type 5233A, Kistler, Winterthur, Switzerland).A sixteen-camera Qualisys motion capture system (500Hz, Oqus 700+, Qualisys AB, Göteborg, Sweden) was used to record reflective marker data for the static trial.

The laboratory pitch length dimensions were the same as a standard cricket pitch (20.12 m), however, within the given constraints of the laboratory space, the pitch width was 2.1m, which is narrower than a standard cricket pitch (3.05m). The participants were asked to pitch the ball at a marked area on the ground 6-8m from the stumps at the batsman's end. Two infrared timing gates (Smart Speed Timing Gate System, Fusion Sport, Sumner Park, Queensland, Australia), spaced 2m apart, were positioned at the estimated point just before the back foot initial ground contact during the pre-delivery stride to measure the pre-delivery approach speed. The bowling run-up distance from the popping crease was measured and marked by the athletes themselves during the warm-up over. The position that the ball hit on the ground was measured using a measuring tape placed along the side of the pitch.

For the purpose of this study five (5) overs of six (6) deliveries each were required to be delivered at competition pace by each participant. Participant were instructed to aim to pitch the ball in the 'good length' area and maintain their average maximum speed throughout the bowling spell. Before commencing the experimental task the participants performed a standardised balance and postural stability warm-up (Bird & Stuart, 2012), as well as six (6) warm-up bowling deliveries at an intensity of 50% of maximum effort. The participants then performed the experimental bowling task. Between each over, there was a non-bowling period of 5 minutes with fielding drills to replicate match conditions, according to the protocol of Schaefer et al. (2018).

The sixteen camera Qualisys motion capture system recorded all movements in three-dimensions (3D) for the experimental tasks. All 3D ground reaction forces (GRFs) generated at front foot-ground landing were measured by the two previously referenced force platforms embedded in the floor.

3.2.5. Data reduction

Visual3D software (Version v6, C-Motion, Germantown, MD) was used to analyse the 3D kinematic and kinetic data for all recorded bowling overs. All raw kinetic and kinematic data were filtered based on recommendations by Bisseling and Hof (2006) and Kristianslund, Krosshaug, and van den Bogert (2012) using a fourth order zero phase Butterworth low-pass digital filter (f_c=50Hz). Peak magnitudes and loading rates of GRFs during FFC were smoothed with a fourth-order zero-phase Butterworth low-pass digital filter (f_c= 18 Hz). Segment masses of the foot, shank, thigh, upper arm, forearm, hand and head were defined according to Zatsiorski (1990), while segment masses for the pelvis, lumbar and thorax segment were defined according to Pearsall, Reid, and Livingston (1996). To model the initial properties of each segment, geometric primitives (Hanavan, 1964) were used; with the pelvis, lumbar region and thorax defined as elliptical cylinders (Seay, Selbie, & Hamill, 2008), the foot, shank, thigh (Ford, Myer, & Hewett, 2007), upper arm, and forearm defined as frusta of a right cone, the hand defined as a sphere and the head defined as an ellipsoid.

To estimate the joint centres the midpoint point between the two markers was used (Table 3.1) (Zatsiorski, 1990). L5- S1 and T12-L1 inter-segmental angle: lumbar segment angles tracked using 5 lumbar tracking markers (appendix 3.6). The shoulder was tracked using markers placed on the acromion process, the anterior aspects of shoulder (5cm inferior to acromion), and posterior aspects of the shoulder (in line with anterior aspects). The sign conventions of the local coordinate system were defined as X-axis is the mediolateral axis, Y-axis is the anterior-posterior axis, and Z-axis is the superior-inferior axis.

Table 3. 1 Midpoint markers to estimate joint centres

Joints	Two markers
Ankle	The lateral and medial malleolus
Knee	Lateral and medial femoral condyles
L5-S1 (kinematic only)	Mid-point between iliac crests
T12-L1	Bilateral rib cage markers at the level of T12-L1
Hip joint centre	25% of the distance from the dominant to the non-dominant greater trochanter
L5-S1 (kinetic only)	5% along the virtual line from L5S1 marker to the bisector of the two ASIS markers
Shoulder	50% distance between the anterior and posterior aspects markers

To express inter segmental ankle, knee, hip, L5S1, T12-L1, elbow, and wrist joint angles and/or moments, x, y, z cardan sequence of rotation were used and z, y, z cardan sequence of rotation were used for the shoulder joint inter segment as reported in Table 3.2.

Table 3.2 The x, y, and z cardan sequence

Joint /Inter Segment	Express / Articulated
Ankle joint	Dorsiflexion-plantarflexion Forefoot adduction-abduction Inversion-eversion
Knee and hip joint	Flexion-extension Abduction-adduction Internal-external rotation
L5-S1 and T12-L1 inter segment	Flexion-extension Left-right lateral flexion Right-left rotation
Elbow inter segment	Flexion-extension, Y-axis cross talk (not reported), Pronation-supination
Wrist inter segment	Flexion-extension, Ulnar-radial deviation, Z-axis cross talk (not reported)
Shoulder (z, y, z cardan sequence)	Flexion-extension, Adduction-abduction Internal-external rotation

Kinetic data from successful trials, where the participant's front foot fully landed on the force plates, were used to calculate individual peak net internal joints moments and forces. Internal joint forces and moments were estimated via inverse dynamics. This computation was performed between front foot initial ground contact and upper arm vertical during the delivery phase. Medial shear force and anterior shear force, as well as vertical compressive force, were defined as positive directions. L5-S1 and T12-L1 joint forces were normalised to the individual's body mass and the peak internal joint moment was normalised to the individual's body mass multiplied by height. The distance between the proximal end of the back-foot segment at back foot initial contact and the proximal end of the front foot segment at the front foot initial contact was measured as step length and normalised to the individual's height.

Individual bowling actions were classified into side-on, front-on, semi-on and mixed according to Ferdinands et al. (2010) guidelines (see section 3.2.7).

3.2.6. Data analysis

For the analysis of kinematic data, the five stages of the bowling action including back foot contact, front foot contact, arm horizontal, ball release and arm vertical, (figure 3.2) were defined automatically using Visual 3D digitisation software, in accordance with Schaefer et al. (2018), and confirmed by visual inspection. The methodology defined by Schaefer et al. (2018) was utilised to determine both back-foot and front-foot initial ground contact (BIC & FIC); time of the peak vertical (F_V), anterior (F_{ANT}), posterior (F_{POST}), medial (F_{MED}) and lateral (F_{LAT}) GRF; front foot-ground take-off (FTO); upper-arm horizontal backwards (AH); ball release (BR); and upper-arm vertically downwards (AV) as mentioned below.

BIC were defined at the maximum acceleration of the fifth metatarsal marker of the back foot in the posterior direction relative to the laboratory coordinate system. The stages of FIC and FTO stages were defined when the vertical GRF exceeded or drop below 10N respectively. The respective peak GRFs between FIC and FTO were used to define the peak GRFs. Peak vertical ground reaction force (F_V) were defined when front foot vertical GRF has reached its maximum peak. AH was defined when BIC when the x-axis of the angle of the upper arm segment relative to the laboratory coordinate system crossed a 90º threshold on the ascent phase. BR was defined when the distance of separation between the ball and the dorsal hand markers of the bowling hand crossed a 0.1m threshold on the ascent phase. AV was defined after FIC when the x-axis of the angle of the upper arm segment relative to the laboratory coordinate system crossed a 0º threshold on the decent phase.

Both rear and front foot alignments were defined as the foot segment relative to the laboratory coordinate system at the time of BIC and FIC, respectively. Segmental alignment angles, such as pelvis alignment, pelvis counter-rotation, shoulder alignment, shoulder counter-rotation, and shoulder-pelvis separation angle at the time of BIC and FIC, were defined according to Ferdinands et al. (2010) as reported in Chapter 1.

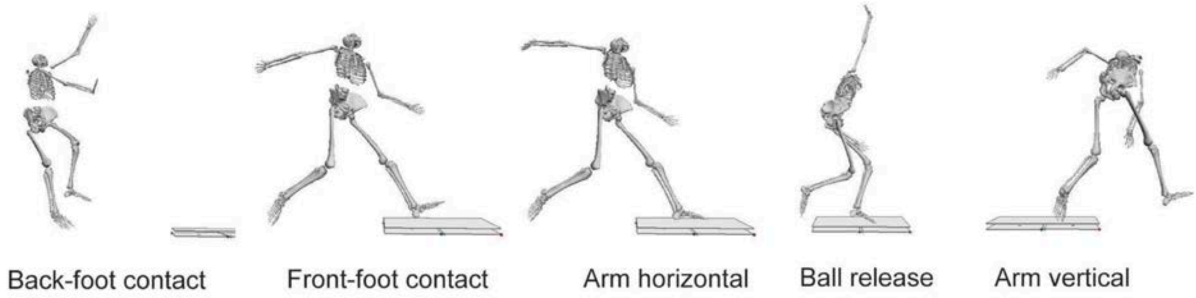


Figure 3.2 Five stages of bowling action. Figure extracted from Schaefer et al. (2018)

The calculation of the net peak internal joint forces and moments was performed between FIC and AV. Only the trials during which the participant's front foot fully landed on the force platforms (76 ± 22%) were considered for the calculations. L5-S1 and T12-L1 joint forces were normalised to body mass (relative BM) and peak net internal joint moments were normalised to the participant's body mass multiplied by height (relative BM x height).

3.2.7. Bowling action classification.

The current study used the bowling action classification system described by Ferdinands et al. (2010) (see section 1.3.1 for further background details). In summary, the bowling actions are classified as follows:

- Side-on: Shoulder alignment < 25º and shoulder counter rotation < 30º.
- Semi-open: 25º ≤ Shoulder alignment < 50º and shoulder counter rotation < 30º.
- Front-on: Shoulder alignment ≥ 50º and shoulder counter rotation < 30º.
- Mixed: Pelvis–shoulder separation angle > 30º or shoulder counter rotation > 30

3.2.8. *Statistical analysis*

Means and standard deviations were calculated for all variables of interest (based on the systematic review) for all successful bowling trials. More than 95% of trails were considered for kinematic variables (97.2 ± 3.8%) (5 overs x 6 deliveries minus those deliveries with missing markers or technical difficulties). Over 75% of trails were considered for kinetic variables (76 ± 22%) (5 overs x 6 deliveries minus those deliveries where the force plate was missed or with missing tracking markers or technical difficulties) for all participants. The prevalence of the biomechanical risk factors for lower back injury in the participants was reported. Descriptives of the DXA variables (bone mineral density, muscle mass and regional distribution) were reported.

The classification of bowling actions of the participants only identified two bowling actions within the group. Therefore comparisons between the two bowling actions were performed using independent t-tests with the significance level set at $P \leq 0.05$. Paired T-tests were also used to compare between the dominant and non-dominant side for DXA variables. All statistical analyses were performed using the statistical analysis software (SAS, version 9.4, SAS Institute Inc., Cary, North Carolina, USA).

3.3. Results

3.3.1. Bowling action classification.

According to the bowling action classification criteria of Ferdinands et al. (2010), (See 1.3.1) out of eleven participants, seven (63.6%) demonstrated a mixed bowling action with a mean value of 39.84º ± 9.22 and 57.12º ± 11.82 for shoulder counter rotation and shoulder alignment angle at BFC, respectively (see Table 3.3). The remaining four (36.4%) participants displayed a semi-open bowling action, with mean values of 20.56º ± 6.28 and 40.61º ± 4.51 for shoulder counter rotation and shoulder alignment angle at BFC, respectively (Table 3.4).

Table 3.3 Bowling action classifications

Bowling Action	Percentage (n=11)	SCR (º)			SA at BFC (º)			SPSA (º)		
		Mean		SD	Mean		SD	Mean		SD
Mixed	63.3% (n=7)	39.84	±	9.22	57.12	±	11.82	14.99	±	11.83
Semi Open	36.4% (n=4)	20.56	±	6.28	40.61	±	3.51	8.77	±	19.26
Front – on	0	-		-	-		-	-		-
Side –On	0	-		-	-		-	-		-

BFC: Back foot contact, SA: Shoulder Alignment, SCR: Shoulder counter rotation, SPSA: Shoulder pelvis separation angle,

3.3.2. Comparison between bowling actions for joint segment angles.

Joint segment angles were reported at three main stages of the delivery stride, first at back foot initial contact (BIC), secondly at front foot initial contact (FFC), and finally at ball release (BR). Seven joint segment angles were observed in total (dominant and non-dominant knee, dominant and non-dominant hip, L5-S1, T12-L1 and shoulder), with three main movement types per joint (Table 3.4).

For knee kinematics, there was significant difference between the mixed bowling action and the semi-open action for left knee adduction (+) / abduction (-) at FFC (P= 0.001), where the angle for mixed bowling action was 8º ± 4.16 and for semi-open was -1.79º ± 2.6. However, there was no significant difference (P = 0.25) observed for the same parameter at BR or for any of the other knee angles. A significantly lower, hip flexion of non-dominant side was observed in the mixed action bowlers (0.94 ± 10.04) compared to the semi-open action bowlers (13.27 ± 6.23) at the FFC (P = 0.03), but not at BIC (P=0.09). When considering the L5-S1 joint segment, there was a significant difference in right rotation of the L5-S1 joint segment between the mixed bowling action and the semi-open bowling action at both BIC (1.02º ± 2.46 vs -2.07º ± 1.1, P=0.02) and BR (0.92º ± 2.76 vs.-2.49º ± 1.74, P=0.03), but not at FFC (P=0.09).

T12-L1 flexion at BR demonstrated a significant difference between the mixed bowling action group (8.34º ± 12.87) and semi-open action group (20.91º ± 4.66, P = 0.04). Also, T12-L1 right rotation at BR displayed a significant difference between the mixed bowling action group (22.1º ± 9.44) and semi-open action group (12.79º ± 2.34, P = 0.04). Furthermore, shoulder adduction and internal rotation at FFC showed significant differences between mixed bowling action (-39.67º ± 14.17 vs. -61.01º ± 12.41, P=0.03) and semi-open bowling action (-25.1º ± 3.33 vs.35.7º ± 3.66, P=0.002). None of the other measured joint segment angles showed significant differences between the mixed and semi-open bowling actions in the junior participant.

Table 3.4 Joint segment kinematics

Segment	Movement	BIC Mixed	BIC Semi-Open	P	FFC Mixed	FFC Semi-Open	P	BR Mixed	BR Semi-Open	P
Back limb knee	Flexion (+) / Extension (-) (^{o})	37.1 ± 14.5	44.31 ± 7.07	0.29	51.81 ± 13.52	63.81 ± 3.83	0.06	- - -	- - -	-
	Adduction (+) / Abduction (-) (^{o})	0.08 ± 9.09	4.12 ± 4.72	0.36	-11.22 ± 8.37	-6.05 ± 7.67	0.33	- - -	- - -	-
	Internal (+) / External (-) rotation (^{o})	1.59 ± 10.1	-0.58 ± 8.82	0.72	-1.6 ± 9.41	-5.9 ± 5.03	0.35	- - -	- - -	-
Back limb hip	Flexion (+) / Extension (-) (^{o})	29.4 ± 9.02	36.38 ± 2.01	0.09	0.94 ± 10.04	13.27 ± 6.23	0.03*	- - -	- - -	-
	Adduction (+) / Abduction (-) (^{o})	-3.52 ± 5.77	0.29 ± 5.12	0.295	-5.1 ± 6.15	-5.06 ± 4.05	0.98	- - -	- - -	-
	Internal (+) / External (-) rotation (^{o})	-5.06 ± 11.7	-0.02 ± 10.24	0.48	1.01 ± 8.8	3.08 ± 9.22	0.72	- - -	- - -	-
Front limb knee	Flexion (+) / Extension (-) (^{o})	- - -	- - -	-	20.95 ± 7.96	16.01 ± 3.96	0.2	50.5 ± 15.8	46.56 ± 25.03	0.79
	Adduction (+) / Abduction (-) (^{o})	- - -	- - -	-	8 ± 4.16	-1.79 ± 2.6	0.001*	3.54 ± 7.99	-1.06 ± 4.33	0.25
	Internal (+) / External (-) rotation (^{o})	- - -	- - -	-	-22.84 ± 11.09	-16.7 ± 3.69	0.22	0.88 ± 8.19	3.97 ± 10.19	0.62
Front limb hip	Flexion (+) / Extension (-) (^{o})	- - -	- - -	-	51.47 ± 4.72	49.97 ± 4.72	0.63	68.3 ± 8.21	72.57 ± 8.25	0.44
	Adduction (+) / Abduction (-) (^{o})	- - -	- - -	-	-33.91 ± 8.93	-28.8 ± 2.06	0.18	-0.83 ± 5.62	1.98 ± 6.46	0.5
	Internal (+) / External (-) rotation (^{o})	- - -	- - -	-	-9.02 ± 6.14	-10.3 ± 6.55	0.76	11.4 ± 5.23	8.11 ± 3.4	0.24
L5-S1	Flexion (+) / Extension (-) (^{o})	-0.39 ± 13.5	-11.3 ± 11.87	0.2	-9.96 ± 14.21	-18.9 ± 9.19	0.24	5.55 ± 15.4	-4.18 ± 12.66	0.29
	Left (+) / Right (-) lateral flexion (^{o})	1.3 ± 2.68	2.56 ± 4.94	0..66	2.37 ± 2.68	3.39 ± 5.55	0.75	3.02 ± 2.2	3.37 ± 4.45	0.89
	Right (+) / Left (-) rotation (^{o})	1.02 ± 2.46	-2.07 ± 1.1	0.02*	3.35 ± 2.13	0.78 ± 2.02	0.09	0.92 ± 2.76	-2.49 ± 1.74	0.03*
T12-L1	Flexion (+) / Extension (-) (^{o})	4.8 ± 13.8	11.9 ± 9.4	0.34	-1.84 ± 16.77	7.93 ± 5.79	0.2	8.34 ± 12.9	20.91 ± 4.66	0.04*
	Left (+) / Right (-) lateral flexion (^{o})	-5.54 ± 6.11	-4.4 ± 6.73	0.72	-0.74 ± 5.12	3.63 ± 4.56	0.19	33.3 ± 4.31	35.24 ± 7.36	0.66
	Right (+) / Left (-) rotation (^{o})	-16 ± 12.3	-7.85 ± 15.29	0.4	21.25 ± 21.02	18.74 ± 5.68	0.77	22.1 ± 9.44	12.79 ± 2.34	0.04*
Shoulder	Flexion (+) / Extension (-) (^{o})	34 ± 18.6	30.18 ± 9.65	0.66	-9.38 ± 15.44	-6.31 ± 12	0.72	-105 ± 82.7	-115.21 ± 29.15	0.77
	Adduction (+) / Abduction (-) (^{o})	2.01 ± 6.07	11.4 ± 10.36	0.17	-39.67 ± 14.17	-25.1 ± 3.33	0.03*	-71.8 ± 8.33	-66.44 ± 13.91	0.52
	Internal (+) / External (-) rotation (^{o})	26.1 ± 15.4	44.34 ± 22.58	0.22	-61.01 ± 12.41	-35.7 ± 3.66	0.002*	-183 ± 86.9	-183.81 ± 39.27	0.99

BIC: Back foot initial contact, BR: Ball release FFC: Front foot contact, *3.3.3. Comparison between bowling actions for segment alignment angles.*

Different parameters of shoulder, pelvis and shoulder/pelvis segments were examined in relation to the bowling actions (see Table 3.6). As a key parameter of bowling action classifications, the mean shoulder counter rotation was higher in mixed action bowlers (39.84º ± 9.23) compared to semi-open action bowlers (20.09° ± 7.96 P=0.003). Similarly, higher shoulder alignment was displayed by the mixed action bowling group (57.12º ± 11.82) compared to semi-open action bowlers (40.61º ± 3.53, P = 0.01) at BIC. Neither the shoulder alignment at peak F_v, nor did any of the other reported segment alignments showed a significant difference between bowling action types (see Table 3.5).

Table 3. 5 Comparison between bowling actions for segment alignment

Segment	Parameter	Mixed action			Semi-open			P
		Mean(º)		SD	Mean(º)		SD	
Shoulder	Shoulder alignment BIC	57.12	±	11.82	40.61	±	3.51	0.01*
	Shoulder alignment Peak F_v	17.57	±	9.85	20.09	±	7.96	0.65
	Shoulder counter rotation	39.84	±	9.23	20.56	±	6.29	0.003*
Pelvis	Pelvis alignment BIC	42.15	±	11.04	32.18	±	19.16	0.39
	Pelvis alignment peak F_v	31.52	±	16.25	23.39	±	23.84	0.57
	Pelvis counter rotation	10.63	±	7.29	8.8	±	5.98	0.66
Shoulder /Pelvis	Pelvis shoulder separation angle BIC	14.99	±	11.83	8.77	±	19.26	0.59
	Pelvis shoulder separation angle FFC	-26.16	±	12.87	-21.5	±	6.83	0.45

BIC: Back foot initial contact, FFC = Front foot contact, F_v; Vertical force at FFC

3.3.4. *Comparison between bowling actions for ground reaction force.*

The mean ground reaction force (GRF) showed no significant difference between the mixed bowling action (3.97 ± 0.96 BM) and the semi-open bowling action (3.91 ± 0.53 BM) (P=0.895).

3.3.5. *Comparison between bowling actions for a maximum joint moment.*

Maximum mean joint moments were measured by relative body mass into height (relative BM x height). The mixed bowling action group demonstrated significantly higher joint moments at hip flexion (1.22 ± 0.65 vs. 0.45 ± 0.37, P=0.03) and at L5-S1 flexion (2.20 ± 0.93 vs. 1.12 ± 0.67, P=0.05) compared to the semi-open bowling action group (see Table 3.6). There were no significant differences in the moments in knee extension, lateral flexion and rotation of the hip and L5-S1. Similarly, no significant differences observed in T12-L1 flexion, lateral flexion and rotation between the bowling actions. However, higher joint moments were observed in mixed action bowlers compared to semi-open bowlers.

Table 3.6 Comparison between bowling action for maximum joint moments (relative BM x height)

Joint moment max (BMm)		Mixed action Mean		Mixed action SD	Semi-open Mean		Semi-open SD	P
Knee	Extension moment	1.46	±	0.16	1.06	±	0.34	0.11
Hip	Flexion moment	1.22	±	0.65	0.45	±	0.37	0.03*
	Lateral flexion moment	3.36	±	0.93	2.94	±	0.58	0.39
	Rotation moment	0.64	±	0.18	0.44	±	0.11	0.06
L5-S1	Flexion moment	2.2	±	0.93	1.12	±	0.67	0.05*
	Lateral flexion moment	1.81	±	0.43	1.04	±	0.36	0.2
	Rotation moment	1.96	±	0.41	1.53	±	0.64	0.42
T12-L1	Flexion moment	1.4	±	0.56	1.23	±	0.24	0.5
	Lateral flexion moment	2.93	±	1.96	1.88	±	0.92	0.27
	Rotation moment	2.22	±	1.26	1.47	±	0.25	0.17

3.3.6. Comparison between bowling actions for joint forces.

As shown in Table 3.7, the joint forces at L5-S1 and T12-L1 did not show significant differences between the mixed bowling action and the semi-open bowling action.

Table 3.7 Joint forces

Joint Force (BW)		Mixed			Semi-open			
		Mean		SD	Mean		SD	P
L5-S1_ Joint Force	Lat	-0.84	±	1.07	-0.5	±	1.33	0.67
	Ant	2.49	±	0.32	2.36	±	0.76	0.76
	Ver	-1.64	±	0.65	-1.6	±	0.48	0.92
T12-L1_Joint Force	Lat	-1.1	±	1.3	-0.5	±	1.89	0.59
	Ant	0.83	±	0.09	0.95	±	0.23	0.38
	Post	-0.81	±	0.28	-0.85	±	0.15	0.71
	Ver	-2.48	±	0.46	-2.53	±	0.56	0.87

Ant: Anterior, Lat: Lateral, Post: Posterior, Ver: Vertical

3.3.7. Comparison between dominant and non-dominant side for bone mineral density

Bone Mineral Density (BMD) was measured for left and right sides of the body for arms, legs and ribs. For these three regions comparisons between the non-dominant side and the dominant side with reference to the bowling arm were performed. BMD for all three regions showed no significant differences between the dominant and non-dominant side (see Table 3.8).

Table 3.8 Comparison between dominant and non-dominant side for BMD

	BMD (g/cm^2)						
Region	Non-dominant			Dominant			p
	Mean		SD	Mean		SD	
Arm	0.74	±	0.05	0.79	±	0.04	0.35
Rib	0.70	±	0.08	0.74	±	0.07	0.87
Legs	1.26	±	0.11	1.25	±	0.12	0.79

3.3.8. Comparison between bowling actions for BMD of different regions of the body.

Besides the regions mentioned in the previous section, BMD was also reported for thoracic spine, lumbar spine, and pelvis. For all BMD regions comparisons between the mixed bowling action group and the semi-open bowling action group were performed. As shown in Table 3.9 no statistically significant differences between the bowling action types were found in BMD for any of the regions.

Table 3.9 Comparison between bowling actions for BMD of different regions of the body.

BMD (g/cm^2)								
Region	Side	Mixed Bowling			Semi-Open Bowling			P
		Mean		SD	Mean		SD	
Arm	Non-dominant	0.74	±	0.06	0.74	±	0.03	0.18
	Dominant	0.80	±	0.04	0.77	±	0.03	0.6
Rib	Non-dominant	0.69	±	0.08	0.71	±	0.07	0.89
	Dominant	0.73	±	0.07	0.76	±	0.07	1
Spine	Thoracic	0.97	±	0.13	0.86	±	0.16	0.63
	Lumbar	1.07	±	0.18	1.03	±	0.13	0.68
Pelvis	-	1.26	±	0.14	1.17	±	0.17	0.63
Leg	Non-dominant	1.29	±	0.11	1.22	±	0.11	0.9
	Dominant	1.28	±	0.13	1.21	±	0.10	0.68

3.3.9. Comparison between dominant and non-dominant side for lean mass.

Lean mass (LM) of both arm and leg regions were compared between the dominant side and the non-dominant side with reference to the bowling arm. No significant differences in LM were found between the dominant and non-dominant side (see Table 3.10).

Table 3.10 Comparison between dominant and non-dominant side for lean mass

	Non-dominant			Dominant			
	Mean (g)		SD	Mean (g)		SD	P
Arm	2677.85	±	413.83	2834.15	±	382.61	0.8
Legs	9019.93	±	734.35	9070.36	±	786.63	0.83

3.3.10. Comparison between bowling actions for lean mass of different regions of the body

No statistically significant differences between the bowling action groups were found for LM of any region of the body (see table 3.11).

Table 3.11 Comparison between bowling actions for lean mass of different regions of the body

Region	Side	Mixed Bowling			Semi-Open Bowling			P
		Mean (g)		SD	Mean (g)		SD	
Arm	Non-dominant	2634.37	±	494.00	2753.95	±	265.78	0.33
	Dominant	2815.74	±	462.10	2866.38	±	242.35	0.31
Trunk		22230.47	±	2277.57	22292.83	±	1608.27	0.61
Leg	Non-dominant	9019.23	±	786.59	9021.15	±	748.42	1
	Dominant	9027.77	±	884.33	9144.90	±	697.80	0.74

3.4. Discussion

The main purpose of this study was to investigate the biomechanical characteristics of male junior fast bowlers. Two main bowling actions were identified (mixed action and semi open action) and comparisons of kinematic and kinetic data between these two groups were performed. Furthermore, regional bone mineral density and muscle distribution DXA scans in junior fast bowlers were also investigated.

3.4.1. Bowling action classifications and segment alignments

The analysis of segment alignment in the current study demonstrated that the majority of the junior fast bowlers (63.6%) used a mixed bowling action, while the rest used the semi-open bowling action (34.4%). These findings agree well with a study conducted with a large group (n=34) of New Zealand senior premier standard fast bowlers, which also reported that the majority (64.7%) of the bowlers used the mixed bowling action and the rest used non-mixed bowling actions (Ferdinands et al., 2010). The mixed bowling action with high shoulder counter rotation, however, has been identified as a high-risk biomechanical factor that is associated with low back injuries based on the studies conducted by Burnett et al. (1996), Hardcastle (1991) and also Portus et al. (2004). All other bowling actions, including semi-open, front-on and side on bowling actions, are considered as safe and effective bowling techniques. It is therefore alarming to find that 7 out of 11 junior fast bowlers in this study still used this high risk mixed bowling action that may lead to serious consequences for the junior fast bowlers ranging from potential minor to serious low back injuries, and early dropout from the game. Shoulder alignment at the BIC also displayed significantly higher readings in the mixed action ($57.12^{o} \pm 11.82^{o}$) compared to the semi-open action ($40.61^{o} \pm 3.51^{o}$). Shoulder pelvis separation angle, however, was comparatively low and showed no significant differences between the mixed ($14.99^{o} \pm 11.83^{o}$) and semi-open ($8.77^{o} \pm 19.26^{o}$) bowling actions. This is a positive finding, as high shoulder pelvis separation angle ($31^{o} \pm 15^{o}$) has been associated with trunk injuries, such as back strain injuries (Portus et al., 2004). Overall the finding of 63.6% of junior fast bowlers using the high risk mixed bowling action is worrying and highlights the importance of focussing on the development of safe fast bowling actions at the junior level.

3.4.2. Kinematic factors.

The systematic review in the previous chapter identified several kinematic factors that have been associated with higher risk of low back pain or injuries. Hip flexion angle was identified as one of the key kinematic factors, as non-injured fast bowlers have been shown to have higher hip flexion angle at FFC (51 ± 6^0) compared to injured fast bowlers (46 ± 6^0) (Bayne et al., 2016). The junior fast bowlers in the current cohort, who had a mixed bowling action, displayed significantly lower dominant side hip flexion angle at FFC compared to that of the semi-open bowling action group (P=0.03). Therefore most of these junior fast bowlers (7 out of 11) are likely to be at a higher risk of getting a low back injury throughout their bowling careers. However, the study by Baine et al. (2016) did not incorporated bowling actions, hence further investigation is needed to improve understanding of the relationship between hip flexion, bowling action and injuries. Furthermore, the difference between flexion of the dominant side and non-dominant side in the current study was large in the mixed bowling action group (50.53^0) compared to the semi-open bowling action group (36.7^0). This finding suggests that bowlers with the mixed action are less flexible on both the dominant and non-dominant side of the body.

Right rotation of the L5-S1 segment was significantly higher in the mixed action bowling group at both BIC (P=0.02) and BR (P=0.03) during the delivery stride compared to the semi-open group. In other words, these bowlers were more front-on at the lumbar and pelvis at FFC and BR than the semi-open bowlers. The nature of the mixed bowling action, where the shoulder and hip are not aligned, and the shoulders are more front on compared to the hip, could be the reason for this higher trunk right rotation. This higher trunk right rotation could be generating higher rotational force or moment to the lower trunk and hip. The L5-S1 segment of the semi-open group was in a more left rotated position at both BIC and BR, which may be due to the shoulder being in a more left rotated alignment at these positions. Even though there were no reported associations of these variables with the risk of low back pain, further studies are warranted to investigate correlation between other kinematic and kinetic variables with low back injuries.

The mixed action bowlers demonstrated significantly lower flexion of T12-L1 compared to that of the semi-open bowling action bowlers at BR. Lower hip flexion of mixed bowling action bowlers at FFC may result in lower flexion of the thoracolumbar region. Higher shoulder counter rotation of mixed bowling action bowlers may be an inverse effect of this lower flexion of hip and T12-L1. There is no reported association between thoracolumbar flexion and low back injuries, however as lower hip flexion and shoulder counter-rotation are identified risk factors, further investigation in thorax flexion is warranted. Lateral flexion of T12-L1 in the thorax region at FFC did not demonstrate any significant differences between the two bowling actions. Both groups also demonstrated comparatively lower (30^0) T12-L1 lateral flexion than previously reported values of injured fast bowlers who displayed greater thorax lateral flexion (above 45^0) (Bayne et al., 2016). Therefore, the findings for T12-L1 lateral flexion in this cohort are at a satisfactory level. However, further analysis of T12-L1 lateral flexion of cricket fast bowling action is highly recommended to investigate any relationships between bowling action kinematics and injury mechanism. Not surprisingly, the mixed bowling action group displayed significantly greater T12-L1 right rotation at BR compared that of the semi-open bowling action group, in other words mixed bowlers were more front on than semi-open bowlers at BR. This could be expected due to quick shoulder realignment from the BIC to BR. Both shoulder adduction and shoulder internal rotation at FFC displayed significant differences between the mixed bowling action and semi-open bowling actions. However, there are no reported associations of shoulder internal rotation and shoulder adduction with lower back injuries in cricket fast bowlers.

Although some of the kinematic factors such as higher shoulder counter rotation, hip flexion, shoulder alignment, and also bowling actions, such as the mixed bowling action, have been identified as high risk by many researchers, the majority of the junior bowlers still demonstrated these risk factors and bowling actions. This is critical, as all these junior bowlers are demonstrating these risk factors at the early stage of their career, which might result in early dropouts from their career due to injury. However, there were also a few significant differences in kinematic factors between the two bowling actions in this cohort, such as front knee adduction, shoulder adduction and shoulder internal rotation, which have no identified association with low back injuries. However, as these factors were demonstrated to be significantly different between the bowling actions, and as mixed action has already been identified as a higher risk bowling action, further investigation of correlations between these kinematic factors with injuries and other identified risk factors is warranted. Moreover, research findings should be simplified and focus on practical applications that can be shared with coaches and athletes and all people practically involved with the game of cricket.

3.4.3. Kinetic factors

In the current study, only the front foot contact kinetics were collected. No significant differences between bowling actions were found for GRF. Similarly, no significant differences were observed in any of the joint forces at L5-S1 and T12-L1 between the bowling actions. This similar nature of the joint forces could be expected as GRF was not significantly different between the bowling actions. In considering the GRF further, no reported relationships between GRF and low back injuries have been observed. Furthermore, these findings indicated that GRF does not affect the bowling action, which agrees with Elliot et al. (1984), who also showed that GRF did not alter the bowling action. However, so far studies have only focussed on fron foot contact and investigated the GRF of the back-foot contact ha snot been investigated. Hence, further investigation of the back-foot contact GRF and its correlations with low back injurers and the bowling action is warranted to clarify of the relationship between GRF, lower back injuries and bowling action.

In considering joint moments, this study found that, L5-S1 flexion moment of mixed bowling action bowlers was significantly higher compared to that of semi-open action bowlers. This may result in a higher magnitude of stress to the lower trunk of the mixed action fast bowlers. Moreover, this is another critical finding for this group of junior fast bowlers, as research has shown that bowlers who suffered from low back injuries had a higher lumbar flexion moment compared to non-injured fast bowlers (Bayne et al., 2016). This similar study also reported that the injured fast bowlers had a higher lumbar lateral flexion moment. In the present study, however, there was no significant difference in L5-S1 lateral flexion moment.

Moreover, the current study found a significantly higher hip flexion moment in the mixed bowling action compared to the semi-open bowling action. The higher difference of front hip flexion and back hip flexion of mixed bowling action bowlers at the FFC compared to that of semi-open action bowlers may have resulted from the higher hip flexion moment in the mixed action bowlers. As the function of the hip is important to transfer energy to the upper body and distal segments, having a higher hip flexion moment could reduce the efficiency of the transfer of energy. Hip flexion moment, however, has not been identified as a biomechanical risk factor for low back injuries, hence further focus on hip flexion moment may be an advantage for performance enhancement and injury reduction.

Another important finding of joint moments that was observed in the present cohort is that mixed action bowlers always demonstrated a higher moment in every measured joint compared to semi-open action bowlers. This indicates that mixed action bowlers have to put in more effort in the sense of joint motions compared to the semi-open action bowlers. Although front foot kinetics have been investigated in many studies, only a few studies have examined back foot kinetics (Hurrion et al., 2000; Portus et al., 2004). Further investigation of kinetic factors during back foot contact is therefore warranted.

3.4.4. Bone mineral density in junior fast bowlers

It has been shown that BMD is improved through sporting activities and that bone mass acquisition decreases the risk of bone stress injuries (Scerpella et al., 2018). To date, however, very limited research has been conducted on bone health in cricket fast bowlers (Lees et al., 2016; Micklesfield et al., 2012) and to the author's knowledge no research has focussed on bone health in junior fast bowlers.

Cricket fast bowling action is a non-symmetrical movement, which may result in different development of the dominant side compared to the non-dominant side. The BMD of junior fast bowlers in this study, however, showed no differences between the dominant and non-dominant side of the body with reference to the bowling arm.

When comparing bowling actions, the rapid shoulder counter rotation of the mixed bowling action bowlers may cause greater load in the thoracic region of the spine than for semi-open action bowlers. Comparison between the bowling actions for BMD in different regions of the body, however, showed no significant differences in the junior fast bowlers. A study conducted by Micklesfield et al. (2012) reported higher BMD in fast bowlers compared to spin bowlers, but didn't compare between fast bowling actions. As low BMD is identified as a risk factor tied to lower extremity injuries such as stress fractures and other consequences associated with overuse injuries further prolonged investigation into bone health of junior fast bowlers and associations with low back injuries over the cricket seasons and years is highly recommended.

3.4.5. *Muscle distribution in junior fast bowlers*

A study conducted with elite youth tennis players reported that muscle in the dominant forearm and upper arm hand were 9-20% larger compared those on the non-dominant side (Ireland et al., 2013). This reflects the effect of non-symmetrical movement patters on the growth patterns of the muscles. However, no significant differences in LM were observed between the dominant and non-dominant side in this cohort. Micklesfield et al. (2012) reported a significant difference in total LM of fast bowlers compared to that of batsmen and spin bowlers. A recent study reported that total combined thickness of abdominal muscle was symmetrical in the fast bowlers with low back pain and was greater on the non-dominant side of the bowlers without low back pain (Gray, Aginsky, Derman, Vaughan, & Hodges, 2016). Moreover, a similar study concluded that having a greater abdominal muscle thickness on the non-dominant side is an advantage for fast bowlers. However, within the present study cohort none of the regions demonstrated any significant difference in LM between the two different bowling actions. As these junior fast bowlers are in the early stages of their career, it is not entirely unexpected to see this pattern of symmetry for LM. However, as there is very limited research related to body composition and injuries of fast bowlers, it is difficult to comment on these findings. Hence longitudinal studies on potential development of muscle asymmetry in junior fast bowlers is warranted.

3.5. Limitations of this study

One of the main limitations of this study was the size of the cohort, as this population represented only the junior male representative cricketers in the area. Laboratory environment was another limitation, as it was unfamiliar for the participants, especially bowling with the reflective markers on their body would have been unfamiliar. Furthermore, the laboratory bowling action was set to replicate the usual bowling action, but only included aiming at a wicket without a batsman in place. This does not replicate usual conditions in a cricket match, but these conditions were kept similar for all participants.

3.6. Conclusion

This study examined the bowling actions used by junior elite fast bowlers and the prevalence of identified biomechanical risk factors of lower back injuries among them. This study confirmed that the majority of the junior fast bowlers (7 out of 11) used the mixed bowling action, even though this action is associated with a high risk of low back injuries. Besides the kinematic factors used to identify the mixed bowling action (shoulder counter rotation and shoulder alignment at BFC), several other kinematic factors showed significant differences between the mixed bowling action and the semi-open bowling action (right hip flexion, L5-S1 right rotation at BFC and BR, T12-L1 flexion and right rotation). Furthermore, identified kinetic risk factor, such as higher L5-S1 flexion moment and also significantly higher hip flexion moment, were also observed in the group of junior fast bowlers with the mixed bowling action. Hence necessary strategies, such as coaching and training interventions, as well as awareness programmes, should be taken to address these biomechanical risk factors comprehensively in the early stage of the cricket career to avoid potentially severe consequences later on. Moreover, researchers should aim to simplify findings and provide clear practical applications for both coaches and athletes, as well as governing bodies involved in decision making in cricket.

Despite the non-symmetrical movement pattern of fast bowling, no significant differences in BMD and LM were found between the dominant and non-dominant side of the body of junior fast bowlers. Furthermore, no significant differences were observed between mixed bowling action and semi-open bowling action groups in both BMD and LM for any region of the body. However, as adolescent fast bowlers have demonstrated asymmetry of abdominal muscles, further prolonged investigations in junior fast bowlers on bone health and muscle distribution are highly recommended.

Chapter 4

Summary and Recommendations

4. Chapter 4. Summary and recommendations

4.1. Summary of major findings

The current study provides an important overview of the findings regarding biomechanical risk factors for low back injury in cricket fast bowling, as well as reporting on the presence of known biomechanical risk factors in a cohort of representative junior cricket fast bowlers. The systematic review (Chapter 2) identified both kinetic and kinematic factors associated with low back injuries in cricket fast bowlers. Higher lumbar lateral flexion power, higher lumbar lateral flexion moment, as well as higher lumbar flexion moments were the identified kinetic factors associated with lower back injuries.

For kinematic factors, higher thorax lateral flexion at FFC and BR, a greater range of thorax lateral flexion, lower hip flexion at FFC and greater pelvis rotation at BR were associated with lower back injuries. Furthermore, greater shoulder counter-rotation and greater shoulder alignment at BFC and BR were identified as important kinematic factors associated with lower back injuries. Due to the different kinematics in the shoulder, it is not surprising that the actual bowling action classification is another important factor to evaluate. The mixed bowling action, characterised by shoulder counter rotation and/or pelvis shoulder separation angle, has been recognised as a high-risk bowling action for lower back injuries.

The biomechanical study of representative junior cricket fast bowlers (Chapter 3) demonstrated that the majority of the study cohort (63%) utilised the mixed bowling action, which has previously been associated with an increased risk of lower back injury. Apart from the higher shoulder counter rotation and higher shoulder alignment angle, which are used to classify bowling action, several of the other identified kinematic and kinetic risk factors were found among junior cricket fast bowlers. The kinematic factors which are known to be associated with low back injuries, such as lower hip flexion at FFC, L5-S1 rotation at BFC and BR, lower

T12-L1 flexion and right rotation, were all demonstrated by the junior cricket fast bowlers. Another identified kinetic risk factor, higher L5-S1 flexion moment was demonstrated by the mixed bowling action junior bowlers. Furthermore, higher hip flexion moment, which is not known to be associated with low back injury, was also found in the junior mixed bowling action fast bowlers when compared to the semi-open action fast bowlers. It is alarming to find these high risk biomechanical factors in the majority of the junior fast bowlers in our study. To avoid potentially severe consequences, including potential lower back injury and resulting disability (modified or lost participation), comprehensive action should be undertaken to minimise or eliminate known kinetic and kinematic biomechanical risk factors from the bowling actions of these athletes, particularly as these athletes are still in their early development as junior fast bowlers. Internationally, cricket governing bodies have already implemented injury risk-reduction changes. For example, by placing limits on the maximum numbers of overs (Australia – 8 overs per session, England – 18 overs per day) that junior fast bowlers can bowl, as well as coaching and training interventions to remediate incorrect bowling actions (Schaefer et al. 2018). However, a similar study concluded that limiting the number of overs only would not reduce the likelihood of low back injuries, as the long term effect of the massed repetitions of bowling with higher risk bowling actions, such as mixed action, would still result in an injury mechanism throughout a season. Hence, further studies are warranted to identify the reasons for the use of the mixed bowling action by the majority of bowlers. Moreover, it is recommended to focus more on strength and conditioning of the fast bowlers and also on working on fundamental motor skills before the actual fast bowling. It would help to develop fast bowlers' skill related fitness and increase the ability to endure the bowling workload. Furthermore, development of proper fundamental skills would allow fast bowlers to achieve a much better bowling technique, The DXA scan results indicated no significant differences in both BMD and LM of any region of the body between the mixed bowling action and the semi open bowling action. So despite the large proportion of mixed action fast bowlers and the likely higher impact of this bowing action on the spine, no differences in BMD were found between the groups. Furthermore, there were also no significant differences in BMD and LM between the dominant and non-dominant side of the body for these junior fast bowlers. However, as these data were collected at the start of the regular playing season and only in a small sample of junior fast bowlers, further longitudinal studies should be undertaken to form a clearer picture of expected changes of BMD and LM over time in a larger study cohort.

4.2. Recommendations for future research

Although important information relating to biomechanical risk factors for low back injury in cricket fast bowlers is reported in this thesis, a number of questions still remain to be addressed. Hence, the following recommendations for future research studies are worthy of consideration. Firstly, the examination of more kinetic factors of cricket fast bowling, especially during the back-foot contact rather than only during the front foot phase is required. More research studies focussing on biomechanics of female cricket fast bowlers and associations with low back injuries are also highly recommended. Furthermore, investigating the relationship of flexibility and joint range of motion of fast bowlers with biomechanical factors of bowling actions would provide important information. Finally, most studies have been conducted in Australia, so further research in other countries, including the sub-continental cricketing nations, such as Bangladesh, India, Pakistan, and Sri Lanka, is highly recommended. The final step of all research is to ensure that information is disseminated and that sport scientists, coaching staff, athletes, as well as governing bodies, are all well informed of the implications of research findings.

5. References

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Appendix

6. Appendices

6.1. Appendix 3.1 Injury history questionnaire

Charles Sturt University
School of Human Movement Studies
FACULTY OF SCIENCE
Panorama Avenue
Bathurst NSW 2795
Australia
Mob. 0457 244 259
Email. schaef_89@hotmail.com

Participant ID: ____________

THE UNIVERSITY OF NEWCASTLE AUSTRALIA

FACULTY OF SCIENCE AND INFORMATION TECHNOLOGY
School of Environmental & Life Sciences
Chittaway Road
Ourimbah NSW 2258
Australia
Ph. (02) 4349 4428
Email Suzi.Edwards@newcastle.edu.au
http://www.newcastle.edu.au/profile/suzi-edwards

INJURY HISTORY QUESTIONNAIRE

INVESTIGATION INTO INJURY MECHANISMS ASSOCIATED WITH JUNIOR FAST BOWLING ACROSS A SEASON.

The following information will be collected for purposes of the research project. All information will remain confidential;

Surname: ____________________ First name: ________________ DOB: ___ / ___ / ___ Age: _________

Address: ____

Phone (H): __________________ (Mob): ________________ Email: ____________________________

Occupation: _____________________________________ Hgt: cm Wgt: kg

Injuries: ____

DETAILS OF LEVEL OF COMPETITION/TRAINING

1. In what age group(s) do you play cricket?

☐ Under 13s ☐ Under 14s ☐ Under 15s ☐ Under 16s ☐ Under 17s

☐ Under 18s ☐ Under 19s ☐ Senior

2. Do you participate in any other sports (tick answer)? ☐ Yes ☐ No

If yes please specify: ____.

3. What level(s) of cricket do you compete in?

☐ Local ☐ District ☐ Zone ☐ State ☐ National

4. How many overs do you complete in a game (on average)?

☐ 2-3 ☐ 4-5 ☐ 6-7 ☐ >7

5. How many hours per week do you train for cricket?

☐ 0-1 ☐ 2-3 ☐ 4-5 ☐ >5

6. How many overs in a spell do you complete in a game (on average)?

☐ 0-1 ☐ 2-3 ☐ 4-5 ☐ >5

7. Do you do any other type of training specifically for your sport other than your cricket training (e.g. weights, plyometrics, running etc)?

☐ Yes ☐ No

If so, lists the types of training and hours of training

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1. List any other physical activity(s) that you are currently involved in on a regular basis (more than once per week)?

HISTORY OF INJURIES

2. Have you ever sustained any major **lower limb injury(s)** (ankle, knee or hip) that required medical attention or disturbed your normal activities for more than one week?
   ☐ Yes ☐ No (If yes, please specify what injuries in the table below)

Lower Limb Injury(s)	**< 12 months**		**1-5 years**		**> 5 years**	
	Right	***Left***	***Right***	***Left***	***Right***	***Left***
Type of Injury						
Severity						
Sport or Activity Occurred						
Level of Sport						

3. Have you ever sustained any major **upper limb injury(s) (shoulder, elbow or wrist)** that required medical attention or disturbed your normal activities for more than one week? (If yes, what injuries)
   ☐ Yes ☐ No (If yes, please specify what injuries in the table below)

Upper Limb Injuries	**< 12 months**		**1-5 years**		**> 5 years**	
	Right	***Left***	***Right***	***Left***	***Right***	***Left***
Type of Injury						
Severity						
Sport or Activity Occurred						
Level of Sport						

4. Do you have any current injury or illness which may impede your participation in the task described in the Participant Information Package?
   ☐ Yes ☐ No

If so, please describe.

5. Have you ever sustained any **back injuries** that required medical attention or disturbed your normal activities for more than one week?

☐ Yes ☐ No (If no, you have now completed this questionnaire)

A. <u>INFORMATION ON PREVIOUS LOWER BACK INJURIES</u>

6. What type(s) of back injury did you sustain?

☐ L4/L5 stress fracture ☐ Bulging intervertebral disc ☐ Spondylolysis ☐ Spondylolisthesis

☐ Pars interarticularis ☐ Other

If other please specify: ____.

7. How many previous lower back injury/times of pain have you sustained?

☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ >5

8. How long did you sustain your last back injury?

☐ 0-3 months ☐ 6 months ☐ 12 months ☐ > 12 months ☐ 1-2 years ☐ >2 years

9. What was the severity of your last back injury?

☐ Minor ☐ Moderate ☐ Serious ☐ Severe

10. For how long were you unable to fully play/train for your last back injury?

☐ 1-3 days ☐ 4-7 days ☐ 1-4 weeks ☐ >4 weeks

11. During what activity(s) did you sustain your last back injury(s)?

☐ Fast bowling ☐ Other, please specify: ____.

12. What type of treatment did you received for the last injury:

☐ surgery ☐ physiotherapy ☐ none ☐ don't know

B. LOWER BACK FUNCTION	Previous week					Typical week had when injury/pain				
SYMPTOMS The following questions cover symptoms that you have experienced from your lower back during the previous week, for **the previous week** or a **typical week when you had lower back injury/pain.**	0-3 days	4-6 days	Everyday			0-3 days	4-6 days	Everyday		
1. Have you ever experienced soreness/ stiffness/ had complaints from your lower back?										
[redacted]	Nothing	A little	Moderate	A lot	Very much	Nothing	A little	Moderate	A lot	Very much
2. How painful is your lower back after training?										
3. How painful is your lower back during training?										
4. How painful is your lower back when you wake up in the morning?										
5. How painful is your lower back if you have been sitting still for a while during the day (e.g. school)?										
[redacted]	Never	Rarely	Sometimes	Often	Always	Never	Rarely	Sometimes	Often	Always
6. How often do you experience pain from your lower back?										
7. Do you often sustain small amounts of pain in your lower back that resolve quickly?										
Report the degree of pain that you have felt from your lower back during **the previous week** or a **typical week when you had lower back injury/pain.**	No pain	A little	Moderate	Considerable	Very painful	No pain	A little	Moderate	Considerable	Very painful
8. Bending of your back?										
9. Lifting heavy objects?										
10. Jogging?										
11. Change of direction while running (e.g. turn to chase cricket ball)?										
12. During your run-up when bowling?										
13. During your bowling action?										
14. Throwing a ball (over-arm)?										
Report the degree of difficulty you experience due to your lower back during **the previous week** or a **typical week when you had lower back injury/pain.**	Nothing	A little	Moderate	A lot	Very much	Nothing	A little	Moderate	A lot	Very much
15. During your run-up when bowling?										
16. During your bowling action?										
17. Throwing a ball (over-arm)?										
QUALITY OF PERFORMANCE The following questions concern how your problems from your lower lack injury limit you during cricket training and/or competition. **Report the degree of difficulty** you experience because of your lower back.	Totally	A lot	Moderate	To some degree	Not at all	Totally	A lot	Moderate	To some degree	Not at all
18. In what degree do you trust your lower back during physical activity?										
19. Do you sometimes limit yourself from performing 100% due to concerns of sustaining a lower back?										
20. Have you changed your way of playing (for instance bowling slower) due to complaints from your lower back?										

6.2. Appendix 3.2 Physiotherapy assessment

Charles Sturt University

School of Human Movement Studies
FACULTY OF SCIENCE
Panorama Avenue
Bathurst NSW 2795
Australia
Mob. 0457 244 259
Email. schaef_89@hotmail.com
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Physiotherapy Lumbar Tests/ Evaluation Results

INVESTIGATIONS INTO INJURY MECHANISMS ASSOCIATED WITH JUNIOR FAST BOWLING ACROSS A SEASON

Range of Motion Assessment		
Lumbar spine	Degrees	
Flexion	60	
Extension	35	
	Left	Right
Lateral flexion	20	20
Rotation	15	15
Hip	Degrees	
	Left	Right
Flexion	120	125
Internal Rotation	40	40
External rotation	30	30

Pain Provocation Tests				
	Pain			
Lumbar Spine	Yes		No	
Repeated Movements			✓	
Combined Movements			✓	
Quadrant Test				
	Left	Right	Left	Right
Single leg Hyperextension			✓	✓
Hip				
	Left	Right	Left	Right
Faber test			✓	✓
Quadrant test			✓	✓
Sacroiliac joint				
	Left	Right	Left	Right
Laslett test			✓	✓

www.csu.edu.au
CRICOS Provider Numbers for Charles Sturt University are 00005F (NSW), 01947G (VIC) and 02960B (ACT). ABN: 83 878 708 551

6.3. Appendix 3.3 Consent form

Charles Sturt University

School of Human Movement Studies
FACULTY OF SCIENCE

Panorama Avenue
Bathurst NSW 2795
Australia

Mob. 0457 244 259
Email. schaef_89@hotmail.com

THE UNIVERSITY OF NEWCASTLE AUSTRALIA

FACULTY OF SCIENCE AND INFORMATION TECHNOLOGY

School of Environmental & Life Sciences

Chittaway Road
Ourimbah NSW 2258
Australia

Ph. (02) 4349 4428
Email. Suzi.Edwards@newcastle.edu.au
http://www.newcastle.edu.au/profile/suzi-edwards

CONSENT FORM

INVESTIGATION INTO INJURY MECHANISMS ASSOCIATED WITH JUNIOR FAST BOWLING ACROSS A SEASON.

Thank you for expressing interest in this research. If you agree to participate in this study, please complete and sign the following Informed Consent form. Should you have any questions regarding this study the Chief Investigators may be contacted at any time.

Dr Suzi Edwards (Principal Investigator) School of Environmental & Life Sciences Faculty of Science & Information Technology The University of Newcastle Chittaway Rd, Ourimbah, NSW, 2258 Tel: (02) 4349 4428 Email: Suzi.Edwards@newcastle.edu.au	Udana Bandara (Associate Investigato) Masters Student School of Environmental & Life Sciences Faculty of Science & Information Technology The University of Newcastle Chittaway Rd, Ourimbah, NSW, 2258 Mob : 0426650924 Email: C3240897@uon.edu.au	Andrew Schaefer (Associate Investigator) PhD Student School of Human Movement Studies Allen House, N1 Faculty of Science Charles Sturt University Panorama Ave, Bathurst, NSW 2795 Mob: 0457 244 259 Email: schaef_89@hotmail.com	Dr Edouard Ferdinands (Associate Investigator) Discipline of Exercise and Sports Science Faculty of Health Sciences University of Sydney 75 East Road, Lidcombe NSW 1825 Tel: (02) 9351 9776 Fax: (02) 9351 9204 Email: edouard.ferdinands@sydney.edu.au

I, ____________________________________ *(print name)* consent to participating in the research project titled "*Investigation into the injury mechanisms associated with junior fast bowling across a season*".

My consent to participate in this research is based on the following terms;

1. The purpose of the research has been explained to me, including the potential risks and discomforts involved.	☐
2. I have read and understood the participation information sheet provided to me, and have retained a copy of the information sheet provided to me.	☐
3. I have been given the opportunity to ask questions about the research and received satisfactory responses to all questions I have asked.	☐
4. I am content that I understand what I will be required to do as research participant.	☐
5. I understand that in the event of an injury all associated costs will lie with me, unless the injury was related solely to the negligence of Charles Sturt University or the University of Newcastle.	☐
6. I agree to undergo MRI of my lower back as part of the research project.	☐
7. I have read and understood the MRI information sheets provided to me, and have retained a copy of the information sheet provided to me.	☐
8. I agree to undergo a DXA scan of their body as part of the research project.	☐
9. I agree to be photographed and videoed of my fast bowling technique throughout the duration of the research project.	☐
10. I understand that any information or personal details gathered in the course of this research about me are confidential and that neither my name nor any other identifying information will be used or published without my written permission.	☐

11. I understand that I can withdraw my consent at any time before, during, or after testing, without any penalty.	☐
12. I nominate the person below as someone that can be contacted on my behalf in the unlikely event of an emergency: Name: ______________________________ Address: ______________________________ Phone: ______________________________	☐
13. I am aware the Charles Sturt University's Human Research Ethics Committee has approved this study. I understand that if I have any complaints or concerns about this research I can contact: **Executive Officer** **Human Research Ethics Committee** **Office of Academic Governance** **Charles Sturt University** **Panorama Avenue** **Bathurst NSW 2795** Phone: (02) 6338 4628 Fax: (02) 6338 4194	☐
14. This project has been approved by the University's Human Research Ethics Committee, Approval No. XXXX. Should you have concerns about your rights as a participant in this research, or you have a complaint about the manner in which the research is conducted, it may be given to the researcher, or, if an independent person is preferred, to the: **Human Research Ethics Officer** **Research Office, The Chancellery** **The University of Newcastle,** **University Drive, Callaghan NSW 2308, Australia** Telephone (02) 4921 6333 Email Human-Ethics@newcastle.edu.au	☐

______________________	______________________	____/____/____
Participant Print Name	*Signed*	*Date*

6.4. Appendix 3.4 Ethical committee approval.

HUMAN RESEARCH ETHICS COMMITTEE

THE UNIVERSITY OF NEWCASTLE AUSTRALIA

Notification of Expedited Approval

To Chief Investigator or Project Supervisor:	**Doctor Suzi Edwards**
Cc Co-investigators / Research Students:	**Mr Sajeewa Herath Mudiyanselage** **Dr Edouard Ferdinands** **Mr Andrew Schaefer**
Re Protocol:	**Investigation into injury mechanisms associated with junior fast bowling across a season (2)**
Date:	**23-May-2017**
Reference No:	**H-2015-0059**

Thank you for your **Variation** submission to the Human Research Ethics Committee (HREC) seeking approval in relation to a variation to the above protocol.

Variation to add Sajeewa Herath Mudiyanselage as a Student Researcher.

Your submission was considered under **Expedited** review by the Ethics Administrator.

I am pleased to advise that the decision on your submission is **Approved** effective **23-May-2017**.

The full Committee will be asked to ratify this decision at its next scheduled meeting. A formal *Certificate of Approval* will be available upon request.

Associate Professor Helen Warren-Forward
Chair, Human Research Ethics Committee

For communications and enquiries:
Human Research Ethics Administration

Research & Innovation Services
Research Integrity Unit
NIER, Block C
The University of Newcastle
Callaghan NSW 2308
T +61 2 492 17894
Human-Ethics@newcastle.edu.au

RIMS website - https://RIMS.newcastle.edu.au/login.asp

Linked University of Newcastle administered funding:

Funding body	Funding project title	First named investigator	Grant Ref
WorkCover Authority of New South Wales/WorkCover Sports Research and Injury Prevention(**)	Correction of bowling technique for prevention of lumbar injury in junior fast bowlers	Edwards, Suzi	G1401475

6.5. Appendix 3.5 Coronary artery disease risk factory stratification.

Charles Sturt University
School of Human Movement Studies
FACULTY OF SCIENCE
Panorama Avenue
Bathurst NSW 2795
Australia
Mob. 0457 244 259
Email. schaef_89@hotmail.com

Participant ID:____________

THE UNIVERSITY OF NEWCASTLE AUSTRALIA
FACULTY OF SCIENCE AND INFORMATION TECHNOLOGY
School of Environmental & Life Sciences
Chittaway Road
Ourimbah NSW 2258
Australia
Ph. (02) 4349 4428
Email. Suzi.Edwards@newcastle.edu.au
http://www.newcastle.edu.au/profile/suzi-edwards

Coronary Artery Disease Risk Factor Stratification

INVESTIGATION INTO INJURY MECHANISMS ASSOCIATED WITH JUNIOR FAST BOWLING ACROSS A SEASON.

The following information will be collected for purposes of the research project. All information will remain confidential;

Coronary Artery Disease Risk Factor Stratification will tell you if you should check with your doctor before you consent and participate to being a subject in the study "*Investigation into injury mechanisms associated with junior fast bowling across a season*". Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly: check YES or NO.

YES	NO	
☐	☐	Family history of heart attack, or sudden death before 55 years of age in father or other male first-degree relative (i.e., brother or son), or before 65 years of age in mother or other first-degree female relative (i.e., sister or daughter)
☐	☐	Current cigarette smoker or have quit within the last 6 months
☐	☐	High blood pressure or on high blood pressure medication
☐	☐	High cholesterol levels
☐	☐	Impaired fasting glucose
☐	☐	Obesity
☐	☐	Sedentary lifestyle

Yes to two or more questions

IF YOU ANSWERED

Talk with your doctor in person. Tell your doctor about the Coronary Artery Disease Risk Factor Stratification and which questions you answered YES. Talk with your doctor about the study, "*Investigation into injury mechanisms associated with junior fast bowling across a season*", that you wish to participate in, and have a medical screening by your doctor. Follow your doctor's advice. If you are able to consent to this study, you will require a letter of consent from your doctor approving your participation in the study.

Yes to less than two questions

IF YOU ANSWERED

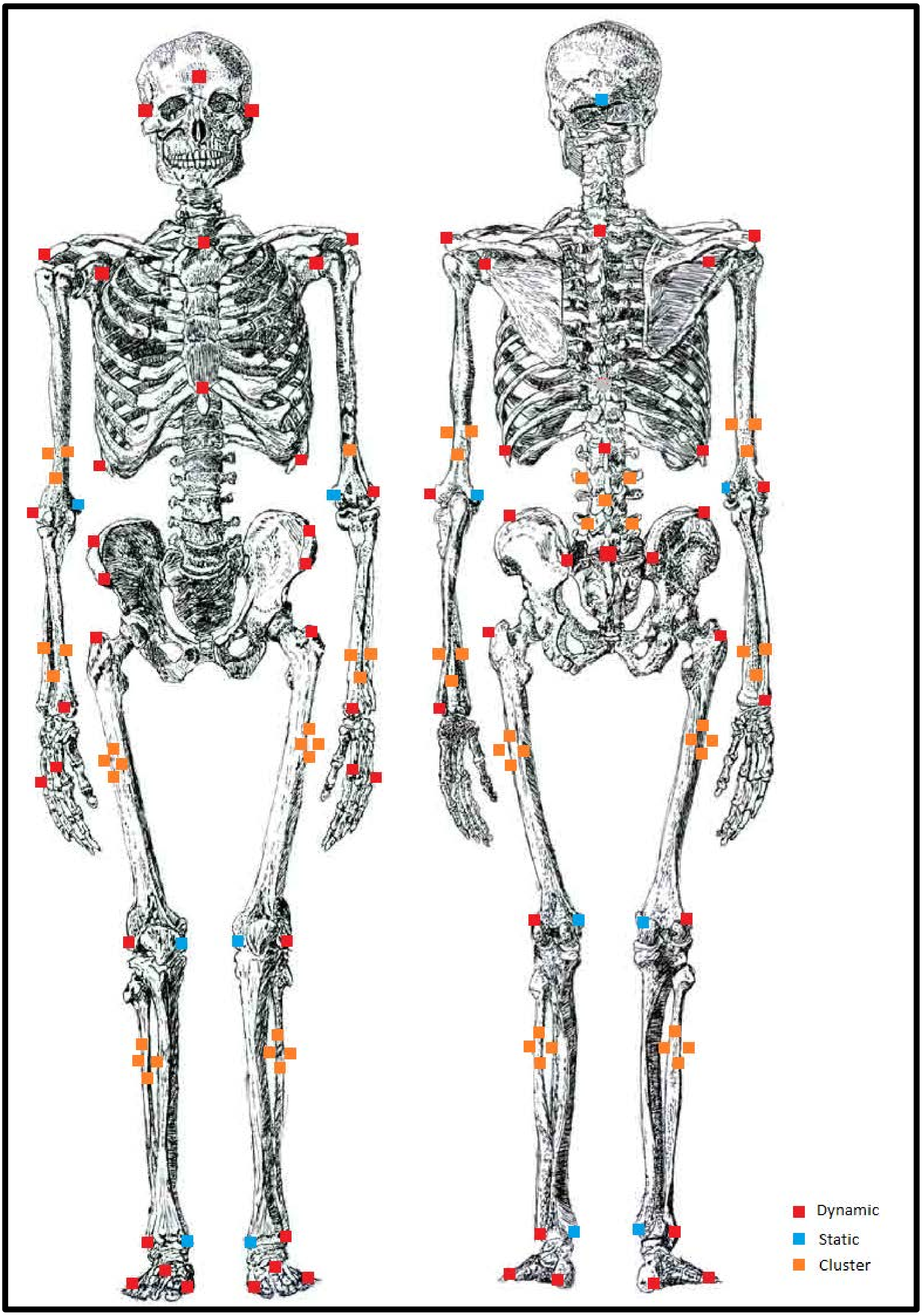
If you answered yes to less than two questions honestly in the Coronary Artery Disease Risk Factor Stratification, you can be reasonably sure that you can become a subject in the study "*Investigation into injury mechanisms associated with junior fast bowling across a season*".

6.6. Appendix 3.6. Marker positions

Investigation into injury mechanisms associated with junior fast bowling across a season.

MARKER POSITIONS

Segment	Marker Positions
Foot	1st metatarsal head 5th metatarsal head Mid-anterior aspect of the foot Calcaneus Medial malleolus Lateral malleolus
Shank	Cluster on the lateral mid tibia (SL,AP,AD) Lateral femoral epicondyle Medial femoral epicondyle
Leg	Greater trochanter Anterior superior iliac spine Iliac crest Posterior superior iliac spine Cluster on the lateral mid-thigh (TL,AP,AD)
Trunk	T12-L1 L5-S1 Cluster on the Lumbar spine Ribcage Sternal notch Xiphoid process Acromion T12-L1 C7
Upper Arm	Posterior shoulder Anterior shoulder Lateral humeral epicondyle Medial humeral epicondyle Cluster on the lateral distal humours
Lower Arm/Hand	Radial styloid Ulna styloid Cluster on the lateral distal forearm dorsal surface of the hand
Head	Forehead Tragus posterior head Crown


Dynamic
Static
Cluster