A multi-factorial evaluation of lower back injury risk factors in fast bowlers

T.J. BARRY

PhD 2021

A multi-factorial evaluation of lower back injury risk factors in fast bowlers

TIMOTHY JAMES BARRY

A thesis submitted in partial fulfilment of the requirements of Manchester Metropolitan University for the degree of Doctor of Philosophy

Department of Sport and Exercise Sciences

2021

Contents

List of figures

List of Tables

Acknowledgements

The wonder and joy of cricket is found in the individual challenges, set within a team environment. It is impossible to succeed without the contribution of your fellow teammates, and similarly the completion of my thesis would not have been possible without the support and assistance of many individuals. May I take this opportunity to continue with the cricket analogy and thank all those who have played an integral role in its completion.

As my chief supervisor, Dr Adrian Burden was the gifted captain, inspirational leader and thoughtful tactician, who encouraged me in every aspect of my work. His excellent advice, attention to detail, unwavering support, ensured that I stuck to my task. He was always there to offer guidance, particularly when I lost my line and length, and I thank him wholeheartedly for all his help. I would also like to express my gratitude to Professor Neil Fowler, Professor Rachel Cooper and Dr Keith Winwood, who all offered alternative strategies on how to succeed when the bowling became hard and the pitch flattened. I am indebted to all the sport science and medical staff at Lancashire County Cricket Club, coaching staff at Cheshire Cricket, Manchester Metropolitan University technical department, past students, and academic colleagues, who have all supported me in data collection. Warmest thanks go to the fast bowlers and participants who gave up their time to participate in the studies. It goes without saying that the research wouldn’t have been possible without them. A special thanks to my brother, David Barry, for his kindness and expertise in reviewing the chapters.

Finally, the whole process of writing a thesis would not have been possible without the unwavering support, patience, encouragement, and unconditional love that my wife, Lindsay Foster, has given me. I thank her from the bottom of my heart.

Abstract

Fast bowlers have consistently been reported to suffer with the greatest frequency of injury, with the lower back being the most common site. The biomechanics of technique, musculoskeletal fitness and workload parameters have all been implicated in the risk of injury. Conversely, aspects of spinal morphology (spinal shrinkage and lumbar curvature) have received little attention, and thus this thesis aimed to investigate whether these should be considered as part of the multifactorial risk of injury to elite fast bowlers.

The Spinal Mouse demonstrated good to high within and between day inter- and intra-rater reliability for measuring sagittal lumbar lordosis, although no acute changes were found after bowling in club standard fast bowlers. Stature measured before, during and after bowling, using a custom-built laboratory stadiometer, resulted in 5-6 mm of spinal shrinkage in club standard fast bowlers. However, this stadiometer did not provide adequate reliability for between-day intra-rater measurements and an alternative device for measuring stature changes in the field was required. The Seca 287 ultrasound stadiometer demonstrated excellent within- and between-day reliability alongside excellent concurrent validity for measuring large stature changes associated with exercise such as fast bowling.

Using the Seca 287 and Spinal Mouse, spinal morphology measurements before and after bowling, were included as injury risk factors alongside three-dimensional kinematics of the bowling action, fitness measures and musculoskeletal function of 14 First-Class county cricket elite fast bowlers. A retrospective analysis of injuries over the 2019 season supported previous research demonstrating that elite fast bowlers experienced a high injury incidence. Bowlers who suffered lower back injuries experienced significantly more spinal shrinkage after five overs of bowling than those who remained injury free (8 ± 1 mm *vs* 4 ± 3 mm), indicating that this may be of clinical significance. Lumbar lordosis of the injured bowlers (31 ± 2°) was not significantly greater than the non-injured bowlers (25 ± 6°), although the effect size was large ($r = 0.5$), indicating its potential importance as an injury risk factor. Biomechanical parameters of the action, fitness measures and musculoskeletal function were not found to be related to lower back injury.

Bowling and physical workload were measured across 4-day, 50 over and T20 cricket formats during the 2019 season in 10 elite bowlers, using GPS units, as additional risk factors. More deliveries were bowled in 4-day and 50 over matches when compared to T20, although adjusting for deliveries per hour resulted in no difference between formats. Intensity of bowling in T20 cricket was perceived to be lower than other game formats, although GPS metrics that calculated changes in acceleration indicated that the T20 format placed an increased intensity on the body when bowling. A lack of high intensity running and sprinting during bowling training sessions was associated with a high injury rate, although bowling workload was not associated with injury to fast bowlers.

This thesis has shown that measures of spinal shrinkage and lumbar lordosis should be added to other injury risk factors measured during pre-season screening. These new risk factors should not be viewed in isolation, but as part of an approach that examines the interrelationships between the factors that could potentially lead to injury. Utilizing big data, machine learning, and a new injury model for fast bowlers may aid future research.

Introduction

Cricket is a popular team sport played in over one hundred countries with the professional game mainly found in those linked to the Commonwealth (Johnstone et al., 2014, McNamara et al., 2015). The game comprises of two teams of eleven players each with a specific role, including fast-bowlers, batsmen, spin bowlers and wicket keepers, with all players also required to undertake fielding activities (McNamara et al. 2015). Cricket is played over three formats (multi-day, one-day and twenty-over), with each taking a different amount of time to complete. Multi-day games include five-day Test matches played at an international level and four-day professional matches (referred to as 'First-class cricket'). These games usually consist of both teams batting twice, with the duration of batting designated as an innings. In each format the bowler will deliver six balls (also referred to as 'deliveries') to a batsman and this is called an 'over' and is the unit by which shorter formats of the game are measured. One-day matches last 50 overs, and the shortest form of cricket involves 20 overs (T20) with both formats consisting of a single innings per team.

Among different playing positions fast bowlers have consistently been reported to have the greatest frequency of injury, with the lower back being the most common site (Langley et al., 2015; Orchard et al., 2015; Alway et al., 2019; Goggins et al., 2020). Research into injury and sport has been influenced by the development of models to aid investigation into the complexity and interaction of associated factors (Bittencourt et al., 2016). These factors have been classified as intrinsic (person related) and extrinsic (environment related) (Olivier et al., 2015). Injury occurs when an internal structure (bone, tendon, ligament, or muscle etc.) fails to cope with the external load applied. Fast bowling applies high loads to bowlers (McNamara et al., 2017), and thus the volume and intensity of bowling (workload) is the major external risk factor. The capacity of a bowler's internal structures to withstand the bowling workload is a key internal factor influencing injury risk. Measurement of the biomechanics of bowling technique, as well as fitness and musculoskeletal parameters have been used to investigate internal risk factors for fast bowlers, alongside workload in different game formats as key external factors (Olivier et al., 2016). Several musculoskeletal screening and fitness tests have been employed to investigate risk of injury to fast bowlers

(Bayne et al., 2015) but measures of shrinkage and curvature of the spine have not been included.

Since the early 1980's, reduction in stature has been used as an index of spinal loading reflecting the creep behaviour of intervertebral discs (IVD), referred to as spinal shrinkage (Dowzer et al.,1998). Moreover, unloading of the spine has shown that a growth in stature may be used as an indirect measure of recovery of IVD height (Healey et al., 2005). Spinal shrinkage research in cricket has been limited to injury-free amateur fast bowlers being investigated (Reilly & Chana 1994; Barry 2007). Other research into spinal morphology has revealed an association between increased lordosis of the lumbar spine and risk of developing lower back injuries in the general population (Been et al., 2009; Kalichmann et al., 2011). However, again, only limited research has been conducted on adolescent amateur cricket bowlers in relation to injury (Hecimovich & Stomski 2016). Despite the early work of Dunlop et al. (1984), who reported that increased lumbar lordosis in combination with loss of IVD height, significantly increased forces that could contribute to lower back injury, no detailed analysis of spinal curvature or shrinkage has ever been included in the analysis of intrinsic injury risk factors for fast bowlers.

This thesis aims to investigate whether spinal shrinkage and lumbar curvature should be considered as internal risk factors for injury to elite fast bowlers. The first chapter reviews the literature on internal and external risk factors associated with injury to fast bowlers, models used to understand the aetiology of injury, as well as spinal morphology. The second chapter examines the effect fast bowling has on spinal shrinkage and curvature, in conjunction with investigations into the reliability of devices used to measure these variables. Further analysis on the reliability and validity of a novel device for more practically measuring spinal shrinkage is presented in the third chapter. Working with elite fast bowlers, Chapter 4 investigates the relationship between spinal shrinkage, lumbar curvature and injury, whilst also exploring associations with other internal risk factors. Chapter 5 analyses bowling workload as the key external risk factor associated with injury over a full First-class season. Chapters two to five are experimental in nature, each structured to include an introduction, methods, results, discussion, and conclusion. The final chapter will review the major findings and provide recommendations for future research.

Overall aim of thesis

To investigate the role of spinal shrinkage and lumbar curvature as part of a multifactorial analysis of injury to elite fast bowlers.

Chapter Aims

Chapter one

To review the literature on injury to fast bowlers in cricket, injury modelling, curvature of the vertebral column and spinal shrinkage.

Chapter two

To investigate the acute effect of fast bowling on spinal shrinkage and curvature of the spine, including an examination of the reliability of current measurement devices.

Chapter three

To investigate the reliability and validity of an ultrasound Stadiometer for measuring stature and spinal shrinkage.

Chapter four

To assess the association between internal risk factors and lumbar injury in a group of elite fast bowlers.

Chapter five

To examine the relationship between injury and workload during a first-class cricket season.

Chapter six

To review the major findings of the thesis and offer recommendations for future research, including the development of a fast-bowling injury aetiology model for cricket.

Chapter 1 - Literature review

This chapter provides a narrative review of injury to fast bowlers in cricket and injury modelling. It focuses on the underpinning mechanisms of injury including biomechanics of the action, workload, and musculoskeletal parameters. The review further explores the literature on the morphology of the spine, specifically on curvature and spinal shrinkage. Since the topic is complex in nature, draws on a number of academic disciplines (exercise physiology, biomechanics, sports medicine) and requires a correspondingly diverse source of literature, a narrative approach has been adopted to allow wider understanding (Greenhalgh et al. 2018).

1.1 Incidence and prevalence of spinal injury in fast bowling

The first reported research into the analysis of fast bowlers was presented by Davis & Blanksby (1976). Interest stemmed from the incidence of multiple lumbar fractures to the great Australian fast bowler Dennis Lillee in the 1970's and the task of rehabilitating him (Pyke et al., 1975). Early research into spine injuries in fast bowlers in cricket was undertaken by Professor Bruce Elliott and his team at the University of Western Australia (Elliott & Foster, 1984). This group published a seminal prospective study of 82 high-performance adolescent fast bowlers and found that 38% of them sustained a lumbar injury during the season, while 11% were diagnosed with a stress fracture of the spine (Foster et al., 1989).

Studies published since the early 1990s continued to demonstrate the high incidence of spinal injuries in senior (Olivier et al., 2013), adolescent (Hardcastle et al., 1992; Burnett et al., 1996; Elliott & Khangure, 2002), elite (Leary & White, 2000; Orchard et al., 2002; Portus et al., 2004; Ranson et al., 2005; Frost & Chalmers, 2014; Alway et al., 2019; Goggins et al., 2020) and club standard fast bowlers (Payne et al., 1987; Ferdinands et al., 2009; Soomro et al., 2018). The epidemiological work of Stretch (2001) in South Africa found that between 38% and 47.4% non-elite young bowlers sustained back injuries, compared with 33.0% to 65.7% in the case of elite bowlers. Further work by the same author followed 436 elite cricketers from all playing positions over three seasons and reported 33.2% of the injuries to fast bowlers, with 47.6% of these injuries in the lumbar region (Stretch 2003). Injuries in the lumbar spine were noted exclusively for bowlers and were not seen in batsmen, fielders and wicket-keepers (Stretch 2003).

In 2005 cricket became the first sport to publish an international consensus statement outlining the methods for injury surveillance among its players (Orchard et al., 2005). This was updated in 2016 and defined injury incidence as the number of new (or new plus recurrent) injuries occurring during matches, training, and the calendar year (Orchard et al., 2016). Recommendations included reporting the incidence of bowling injuries in matches or training per 10 000 deliveries, as well as annual injuries per 100 players per year. Injury prevalence measures were defined as the average number of squad players not available for selection during matches due to injury, or over a 365-day period, presented as a percentage (Orchard et al., 2016).

Using these consensus guidelines in a prospective injury surveillance study conducted over five years including all 18 first class English counties, Langley et al. (2015) found that when comparing the occurrence of different types of injury, bowling injuries had the highest incidence (5 per team per 100 days), with prevalence at 8% and a mean of 37 days lost to injury. Further epidemiological injury analysis of 507 elite cricketers in England between 2010 and 2018 confirmed that bowling related lumbar injuries had the highest prevalence of all recorded injury types with an average of 1.3% of players unavailable for this reason on any given day during the season (Goggins et al., 2020). These findings supported those of Orchard et al. (2016), who had reported a 1.9% injury prevalence for lumbar stress fracture accounting for 15% of all missed playing time across ten seasons of elite cricket in Australia.

Further exploration of the nature and location of injuries to the spine has highlighted the severity of bone and disc injury to the lumbar area. A number of studies reported 24-54% of younger bowlers (ages 13-18) with pars interarticularis defects (Hardcastle et al., 1992; Engstrom & Walker, 2007; Bayne et al., 2015), a far higher incidence than among the general Caucasian population (5-7%) (Fredrickson et al., 1984). The increased risk of lumbar stress fracture at a younger age has been supported by the longitudinal work of Alway et al. (2019) who followed 368 professional English fast bowlers between 2010-2016. An annual incidence of lumbar stress fracture of 4.9 per 100 fast bowlers was found in the 18-22 years age group compared to 2.46 for all bowlers, and the match incidence was 0.13 per 10 000 deliveries with a prevalence of 1.67% of squad days being missed.

Elliott and his team demonstrated that young bowlers with a mean age of 13.7 years had a 21% incidence of lumbar disc degeneration or herniation, which increased to 65% for a group of 18-year-old bowlers (Elliott et al., 1992; Elliott et al., 1993; Elliott & Khangure, 2002). Similarly, Crewe et al. (2012) found that bowlers under 15 years had a prevalence of 21-35% that increased to 43-58% for those over 15. These results suggest that the increase in the incidence of lumbar injury is non-linear with increasing age through the adolescent years. This could be linked to changes in the biomechanics of the action, workload increases, increased force absorption, bone mineral changes and morphology development but no research has confirmed the exact mechanism (Elliott et al., 1992; Elliott et al., 1993; Elliott & Khangure, 2002; Crewe et al., 2012).

Research using MRI to investigate the location and severity of disc degeneration has demonstrated that the lowest two lumber discs were the most common sites of degeneration (Ranson et al., 2005; Crewe et al., 2012; Alway et al., 2019). Ranson et al (2005) showed severe disc degeneration in 12 of the 36 fast bowlers studied with 17% occurring in more than one disc, whilst Crewe et al. (2012) found that only one (4%) of the bowlers had severe degeneration and 52% had moderate severity. Although both studies used the same radiological guidelines and independent radiologists to examine the scans, the difference may be explained by the younger mean age of bowlers (16.1 years) tested by Crewe et al. (2012) compared to Ranson et al ’s (2005) bowlers (mean of 26 years). The cumulative spinal loading and workload of older bowlers could be associated with higher prevalence of bone and disc abnormalities.

Ranson et al. (2005) further noted that a loss of disc height associated with degeneration could lead to increased stress being placed on the posterior bony elements of the lumbar spine. However, further work reported that the discs of 42.9% of fast bowlers who had a chronic stress reaction and lumbar stress fracture were of normal height and appearance

(Ranson et al., 2010). Interestingly among bowlers, disc degeneration did not correlate well with low back pain, but those with chronic bilateral stress fractures (spondolylolithesis) displayed severe disc degeneration at the corresponding spinal level. Whether the stress fracture led to disc degeneration or vice versa was not possible to ascertain (Ranson et al., 2010).

Other research by Ranson et al. (2007) highlighted that junior fast bowlers appeared to develop bone problems before disc degeneration and emphasised the need to use imaging modalities to establish the relationship between acute changes in healthy intervertebral discs and lumbar stress injury. Due to the logistical and financial viability of regular screening, MRI has not been used in cricket to measure acute disc height changes (Ranson et al., 2010). Acute changes in disc height (spinal shrinkage) can be measured indirectly through the use of stadiometry to determine stature loss (Reilly et al., 1988). However, no previous research has investigated shrinkage of healthy discs as a potential mechanism for injury, and no literature currently exists on shrinkage among fast bowlers in relation to injury, thus providing a clear rationale for the studies in this thesis.

As noted above, cricket has led the way in world sport in developing a framework for injury surveillance to aid the reporting of injury incidence and prevalence (Orchard et al., 2005; Orchard et al., 2016). The extent of the lumbar injury problem among fast bowlers is clear but to help explore the cause of these injuries and to be able to predict them, the utilisation of injury aetiology models may be useful (Meeuwisse, 1994). Only one study in cricket has explicitly highlighted the use of such a model (Bayne et al., 2015), thus further exploration is warranted.

1.2 Injury modelling

Researchers have argued that the nature of sports injury is complex and multifactorial, caused by the interaction of many risk factors (Meeuwisse, 1994; Bahr & Krosshaug, 2005; Bittencourt et al., 2016). Early injury research proposed the stress-strain-capacity model, where stress is influenced by external factors while the capacity of bodily tissues to cope with load is subject to internal factors (Meeuwisse, 1994). Van Mechelen et al. (1992) recommended a four-step sequence model for sports injury prevention forming a foundation for future models (Finch, 2006; Bolling et al., 2018). The four steps involved measuring the extent of the injury problem, investigating the mechanism of injury, introducing preventative measures, and finally reflecting on the success of the prevention by measuring injury incidence again (see Figure 1.1).

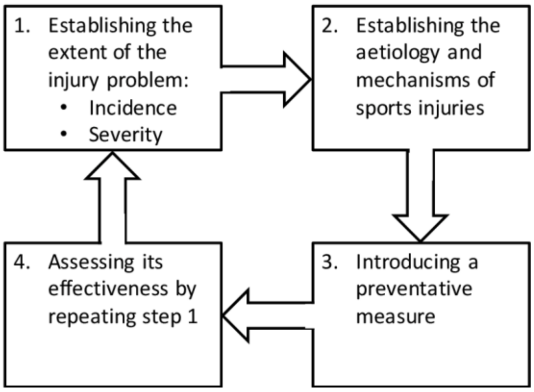


Figure 1.1 - Injury prevention model (Van Mechelen et al., 1992)

More comprehensive frameworks have since been developed to explore the steps in greater detail including the multifactorial aetiology of sports injury model by Meeuwisse (1994) (see Figure 1.2). This model emphasised how multiple factors interact to examine causation in athletic injury. It highlights how intrinsic factors may determine the level of risk to the athlete, but exposure to extrinsic factors will make the athlete more susceptible to an event that might cause an injury.

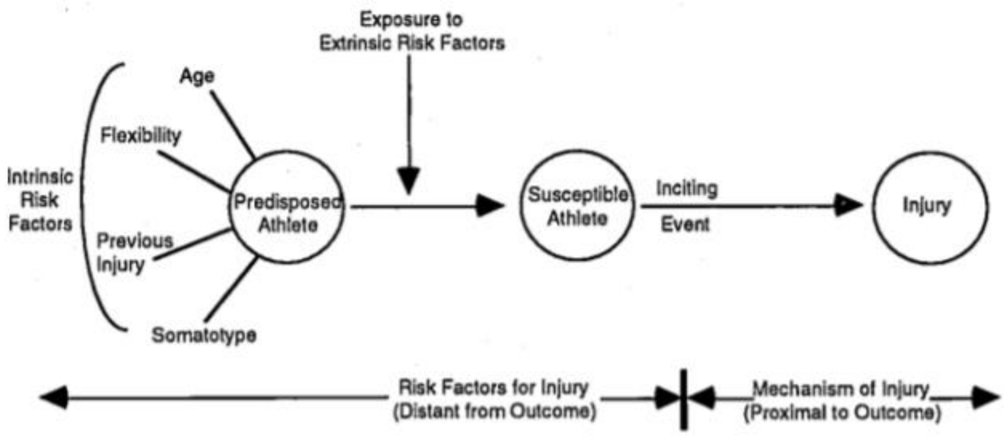


Figure 1.2 - A new multifactorial model of athletic injury aetiology (Meuwisse, 1994)

Further improvements of the multifactorial model included a focus on biomechanics

(McIntosh, 2005; Hewett and Bates, 2017) (see Figure 1.3). Bahr and Krosshaug (2005) combined aspects of Meeuwisse's and McIntosh's models emphasising that internal and external risk factors needed to be considered together at the time of injury. The authors suggested that the biomechanical properties of the inciting event should be thoroughly analysed to augment injury prevention research (see Figure 1.4). Further additions to injury modelling included the recurrence of injury and an emphasis on injury risk as dynamic, rather than linear in nature (Meeuwisse et al., 2007) (see Figure 1.5).

Wind & Gabbett (2017) further developed Meeuwisse et al's (2007) recursive model to emphasise workload (see Figure 1.6), characterising this as the vehicle by which athletes were exposed to external risk factors and potential inciting events. As well as exposure to external factors, workload influenced subsequent risk via modifiable internal risk factors such as fatigue and fitness.

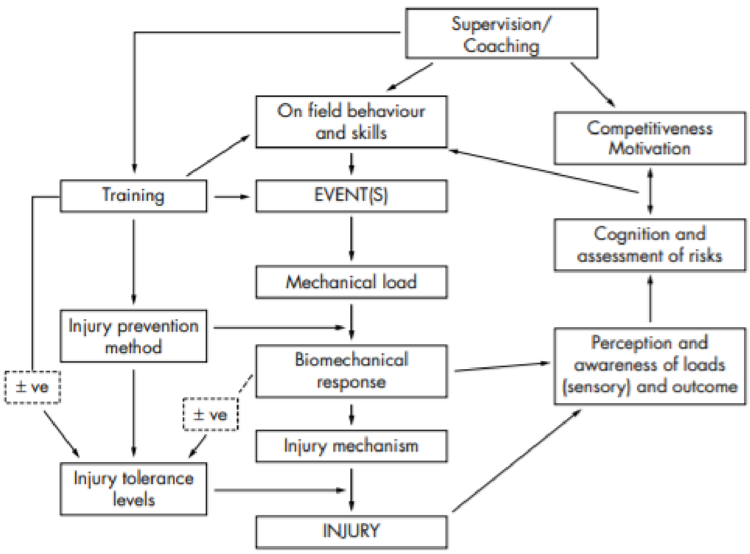


Figure 1.3 - Sport injury model – biomechanical focus (McIntosh, 2005)

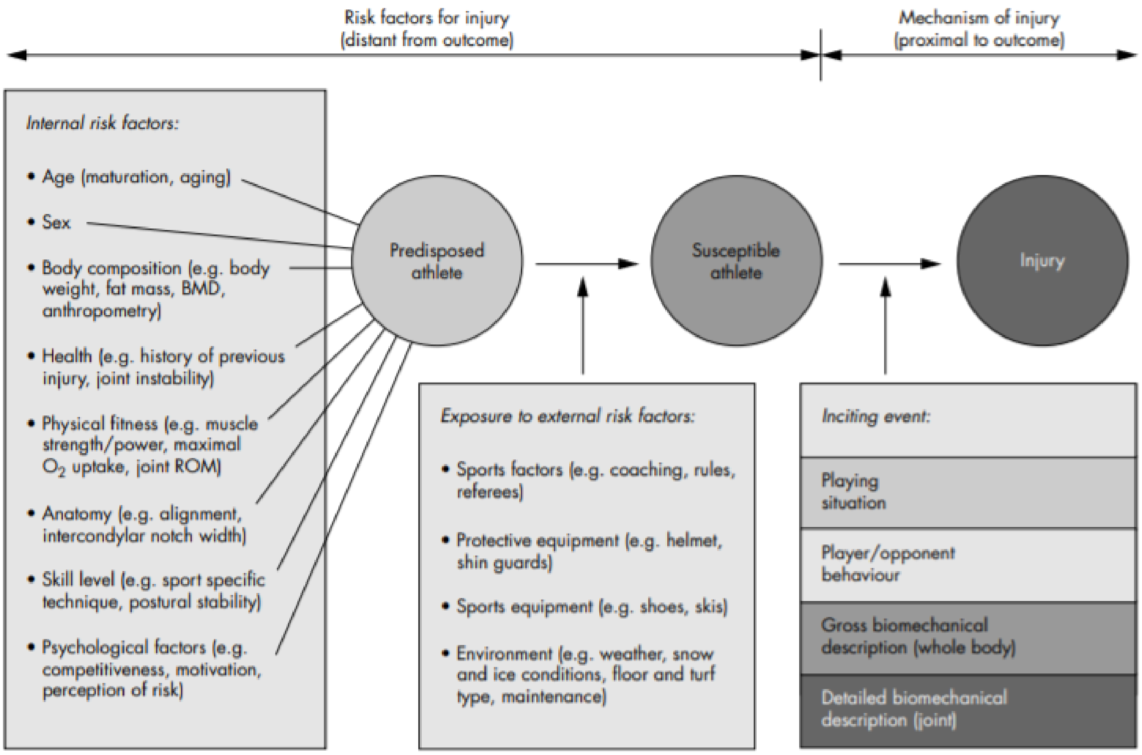


Figure 1.4 – Comprehensive model for injury causation (Bahr & Krosshaug 2005)

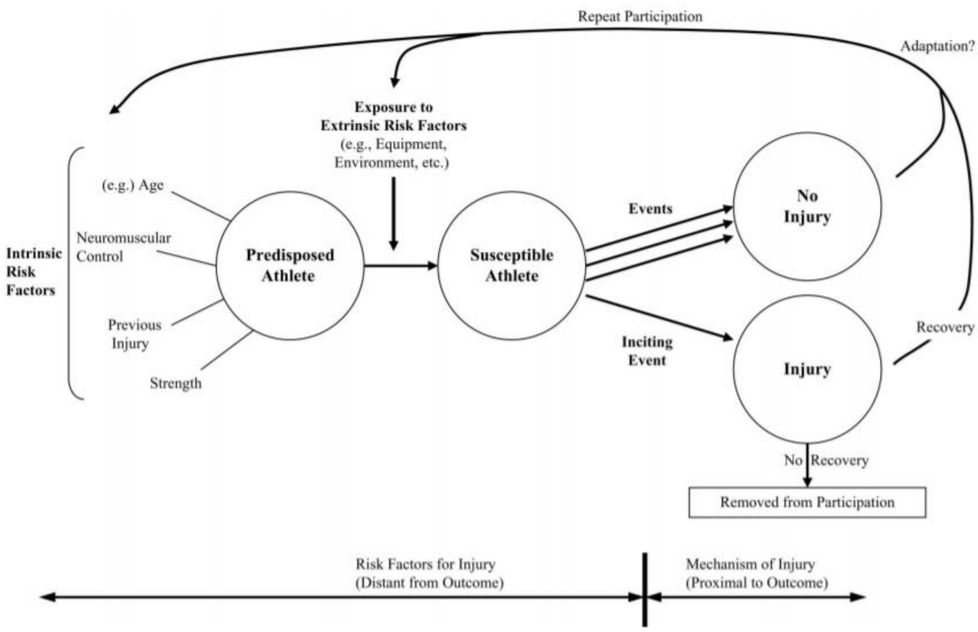


Figure 1.5 - A dynamic, recursive model of aetiology in sport injury (Meeuwisse et al., 2007)

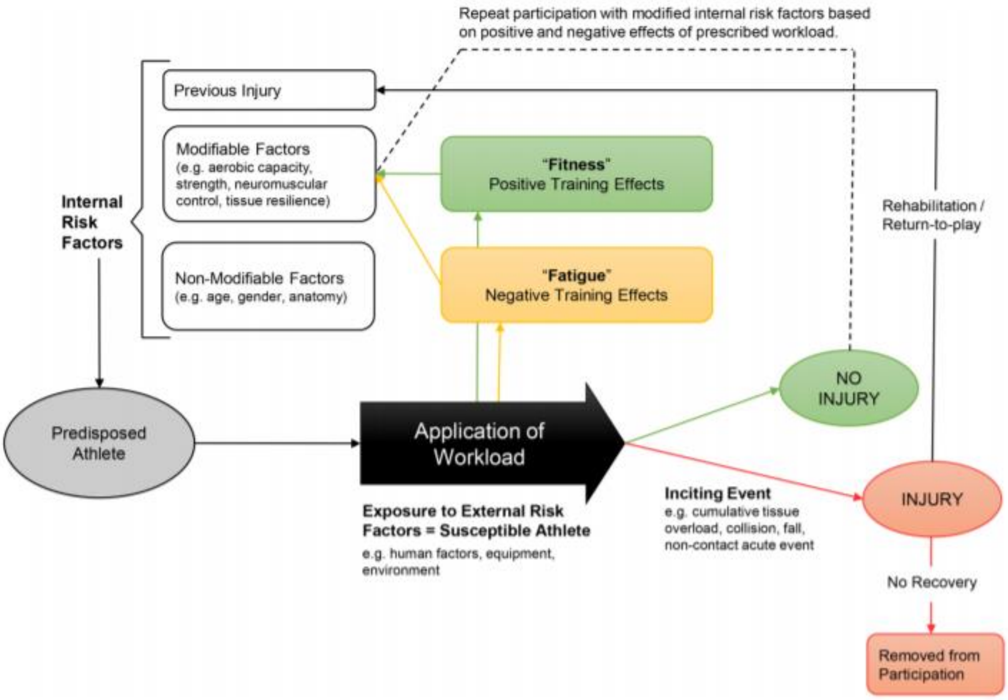


Figure 1.6 - Workload – Injury aetiology model (Windt & Gabbett 2017)

More recently a simplified model of load tolerance and load application was developed by Kalkhoven et al. (2020). The six-layer model (see Figure 1.7) considers how bodily tissues cope with stress, defined as 'internal forces experienced by a structure' and strain defined as 'the amount of deformation or length change in the direction of an applied force.' This simplified model sought to provide a pathway for causation of injury integrating physiological and mechanical characteristics of the human body whilst also incorporating the external forces applied that when excessive, may result in injury (Kalkhoven et al., 2020).

Complexity and dynamism have been highlighted as integral components of sport injury research (Bittencourt et al., 2016; Pol et al., 2019). The move towards a complex systems approach arose from the assertion that the aetiology of injuries arises from the interactions between the risk factors rather than from any one risk factor in isolation. Bittencourt et al. (2016) developed a model to highlight these interrelationships in a non-linear fashion (see Figure 1.8). The non-linear interaction implies that conventional univariate and multivariate regression analysis may not capture the dynamic and complex interplay of risk factors (Ruddy et al., 2019). This is not to say that the reductionist approach is not crucial in establishing individual associations between risk factors and injury, but that it should be used as part of a complex systems approach for further research (Ruddy et al., 2019). The shifting paradigm towards complexity and growth of data linked to injury will necessitate that researchers review methodologies and the formulation of research questions (Nielson et al., 2020).

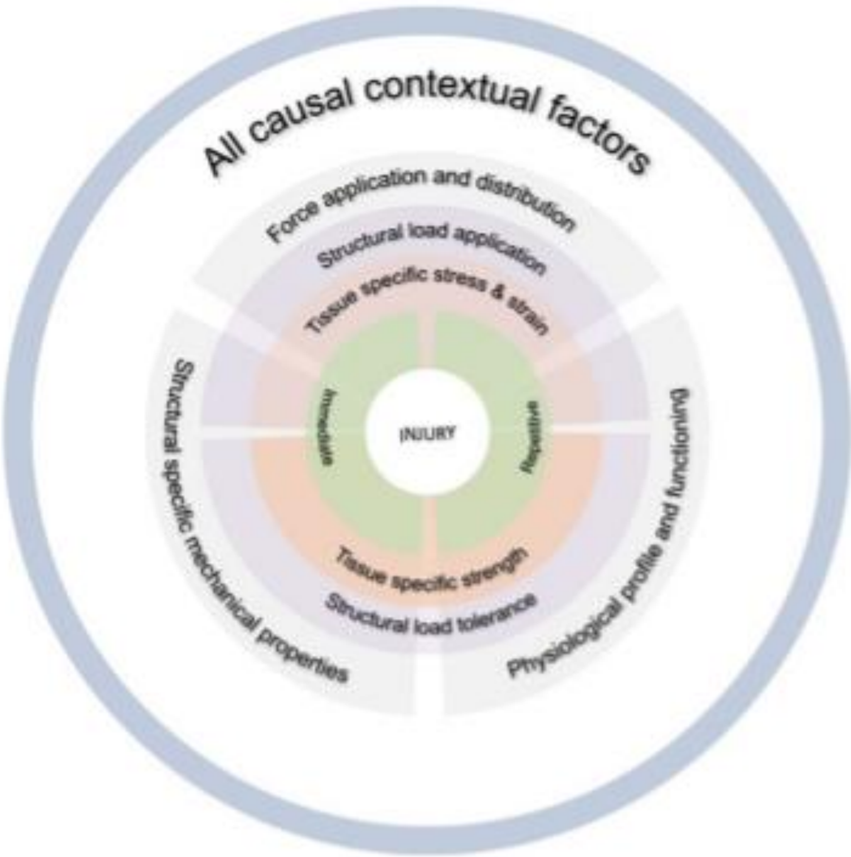


Figure 1.7 - A conceptual model for athlete injury (Kalkhoven et al., 2020)

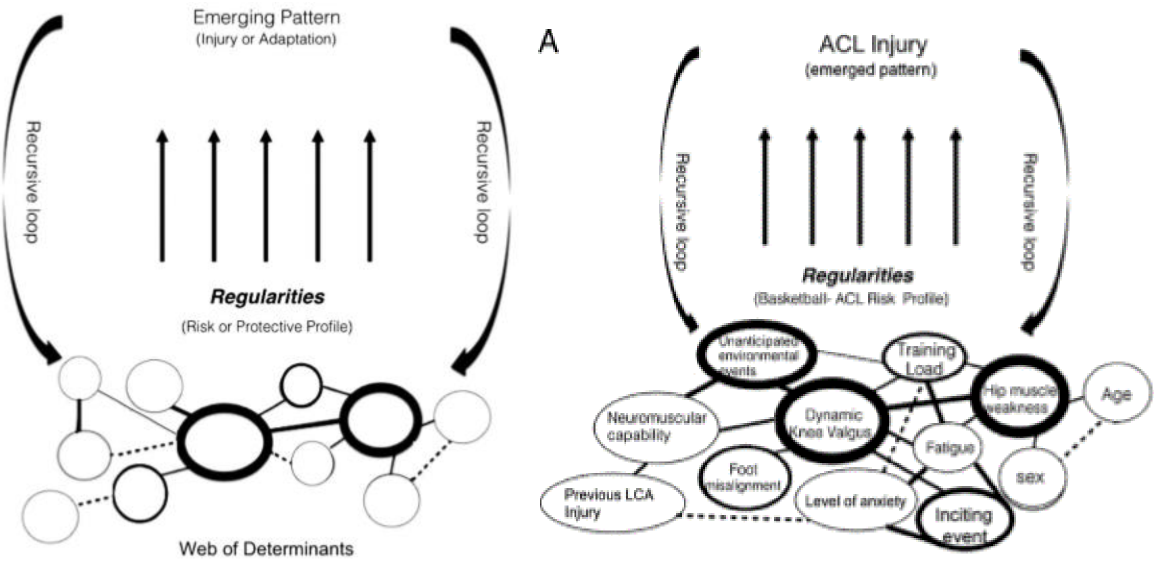


Figure 1.8 - Complex model of sports injury (Bittencourt et al., 2016)

Research into fast bowling injury in cricket has tended to isolate risk factors in the identification process (Bayne et al., 2015; Morton et al., 2013; Olivier et al., 2016). Edouard & Ford (2020) emphasised that understanding the causation of sporting injuries can be aided by the use of injury aetiology models, but only one study in cricket has explicitly highlighted the use of such a model (Bayne et al., 2015). The application of a complex system analysis to cricket may reveal, for example, that two players respond differently to the same set of risk factors, with the result that the researcher may want to find out 'How much bowling is *too much* or *too little* before fast bowlers with different characteristics sustain an injury? These characteristics can be biomechanical, psychological, physiological, and environmental; they will require the researcher to be selective about the use of injury risk variables (Bittencourt et al., 2016; Nielsen et al., 2019). The aim for cricket research should be to develop risk profiles and provide a personalised injury prevention programme, giving bowlers with specific characteristics different training advice. Bertelsen et al. (2017) have suggested that there is a growing need for individual sports to develop their own injury models, and cricket may benefit from such a recommendation. It may be pertinent to go one or two steps further and to try and identify injury models for different playing positions within cricket, moving even further towards a more personalised approach to injury prevention.

1.3 Mechanisms associated with spinal injury in fast bowlers.

Olivier et al. (2016) adopted an internal/external binary classification of injury risk factors with reference to fast bowlers. Intrinsic factors included the biomechanics of technique used during bowling and musculoskeletal measures such as muscle strength, flexibility, back muscle asymmetry, foot arch height and hip range of motion. Extrinsic factors were environment related such as bowling workload (number of deliveries bowled), game type and length (from five-day tests to 20 over format) and context of the game (bowling in first or second innings). The binary approach has included the major risk factors shown to be associated with injury to fast bowlers, in the published literature from over thirty years (Olivier et al., 2016). However, the classification did not include developmental issues such as differences in bone mineral density (BMD) in areas of the spine and growth spurts during puberty that have recently been implicated in the aetiology of fast bowler spinal injuries (Micklesfield et al., 2012; Lees et al., 2016; Alway et al., 2019). Spinal morphology has also been absent from the research on fast bowling injury risk factors. Given the complex interrelationship of all these factors future models of injury risk need to be developed to allow a more nuanced analysis of fast bowling injury.

1.3.1 The biomechanics of technique

Early research used kinematic analysis to classify the fast bowler's action into front-on and side-on (Elliott & Foster 1984; Elliott et al., 1986; Elliott et al., 1990). Both actions were characterised by the hips and shoulders being in alignment at back foot impact with no major deviation from this until ball release. Elliott et al. (1992) later focussed classification on the counter-rotation of the shoulders during the delivery stride, which they thought occurred in an endeavour to improve the side-on position of the shoulder alignment between back foot and front foot impact. The same authors proposed that counter rotation placed stress on the lower lumbar vertebrae (Elliott et al., 1992). Foster et al's (1989) prospective study found that bowlers who counter rotated their shoulders more than 40 degrees from the shoulder alignment at back foot impact (BFI) to a more side-on position were more likely to sustain back injuries, with 11% recording a lumbar stress fracture and 21% a muscle strain to the back. The authors were not able to state whether these defects existed prior to the season but the bowlers were asymptomatic.

A new classification of the bowling action emerged in the 1990's as researchers focussed on shoulder counter rotation (SCR) as a key risk factor in the development of spine injury. Four distinct bowling techniques: side-on, front-on, mid-way and mixed actions were described in the literature (Foster and Elliot, 1989; Burnett et al., 1995; Bartlett et al., 1996). Classification was based on the relationships between shoulder angle at back foot contact, SCR and pelvis-shoulder separation at back foot contact (Portus et al., 2004) (see Figure 1.9 and Table 1.1)

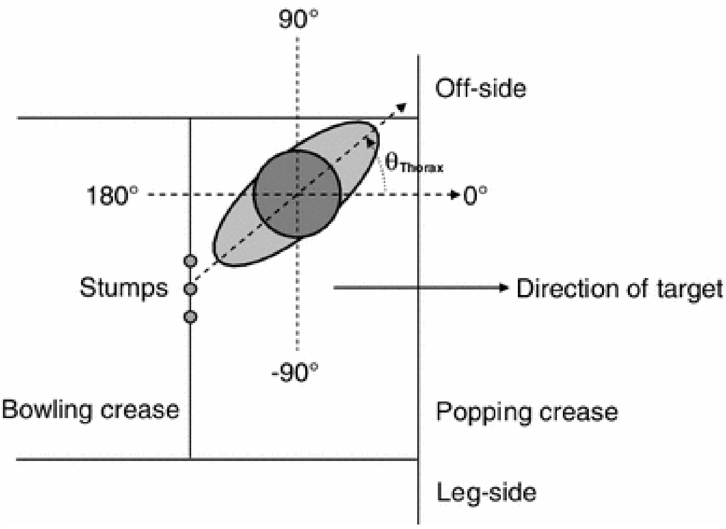


Figure 1.9 - Angles used in classifying bowling action in a right-handed bowler. (Glazier & Wheat 2014) (-90° equates to 270° - see Table 1.1)

Table 1.1 Fast bowling action classification variables (Portus et al., 2004)

Action Type	Back foot contact shoulder angle	Shoulder counter-rotation	Back foot contact pelvis-shoulder separation
Front-on	>240°	<30°	<30°
Mid-way	240-210°	<30°	<30°
Side-on	<210°	<30°	<30°
Mixed	NA	≥30°	≥30°

In defining the mixed action, Foster et al. (1989) identified counter rotation of 30° or greater as an observable movement characteristic these movements were correlated with disc degeneration in fast bowlers.

Stockhill & Barlett (1996) argued that shoulder counter rotation was not a good indicator of lumbar torsional stress especially when the spine was laterally flexed and hyperextended, as occurs in the bowling action. Burnett et al. (1998) addressed this limitation by using an electromagnetic device (Fastrack - 3-Space®Fastrak™) attached to the lumbar spine. In 20 fast bowlers, greater contralateral flexion, angular velocity of the trunk and a more extended spine at front foot impact (FFI) were discovered in those with a mixed action. Improvements in digital image-based approaches including the development of opto-reflective systems such as Vicon, high camera resolution and greater capture rates allowed more detailed analysis of trunk motion to be studied (Elliott & Alderson 2007). Using the Vicon system Ranson et al. (2008), reported no significant range of motion differences in lumbar kinematic variables between the mixed and non-mixed bowling actions. A recent prospective study of 50 elite fast bowlers has supported the assertion that increased lumbopelvic extension at FFI increases the risk of sustaining a lumbar bone stress injury (Alway et al., 2020).

Researchers began to question the importance of the mixed action as an injury risk factor, as the large forces experienced by the spine were occurring during and after the FFI in the delivery stride (Ranson, et al 2008; Ferdinands et al., 2009). Ranson et al. (2008), whilst showing SCR was high, found that the lower trunk was in a relatively neutral position between back foot impact (BFI) and FFI. Ferdinands et al. (2009) found no correlation between SCR and lumbar extension, and only a small proportion of the full range of motion of extension was used during the delivery stride (26%), thereby questioning the importance of this movement in the aetiology of lumbar stress injuries.

Lateral trunk flexion to the non-bowling side at FFI has been highlighted as an important risk factor in the aetiology of lumbar spinal injury. Ranson et al. (2008) stated that extreme lateral flexion during early FFI in the bowling action was 1.3 times the standing range of motion, whilst Ferdinands et al. (2009) noted considerable lumbar bending utilising 74.3 ±

16.6% of the available range of motion. Furthermore, Bayne et al. (2015) reported that greater lateral flexion at ball release (BR) (50° ± 6° vs 40° ± 8°) was associated with lumbar stress injury in fast bowlers. More recent research has confirmed the importance of lumbopelvic lateral flexion at ball release as a risk factor for lumbar bone stress injury (Alway et al., 2020).

Previous studies have developed musculoskeletal models of the lumbar spine to estimate loading during bowling (Ferdinands et al., 2009; Crewe et al., 2012). Ferdinands et al. (2009) noted a relatively small extension of the lumbar spine during the early phase of delivery (BFI to FFI), but found large flexion torques (160 ± .3 Nm) as the lumbar spine coped with a combination of high load and angular velocity from FFI to ball release (power phase). Crewe et al. (2012) reported lumbar rotation and lateral flexion (BFI to FFI), and lumbar rotation (FFI – BR) were significantly correlated with SCR. High flexion (20 $Nm·kg^{-1}$), lateral flexion (25·7 $Nm.kg^{-1}$) and right rotation (20·7 $Nm·kg^{-1}$) torques were recorded leading the authors to suggest that measuring SCR could be used to indicate lumbar loads. A recent prospective analysis of 25 adolescent fast bowlers which utilised Crewe et al's (2012) model, found that those with greater lumbar flexion (10.5 ± 4.9 $Nm.kg^{-1}$ m^{-1} vs 6.9 ± 2.5 $Nm.kg^{-1}$ m^{-1}) and lateral flexion moments (12.5 ± 2.6 $Nm·kg^{-1}$ m^{-1} vs 10.6 ± 1.9 $Nm·kg^{-1}$ m^{-1}) were at increased injury risk (Bayne et al., 2015). Large amounts of contralateral side flexion and rotation continue to be highlighted as principal risk factors, but the threshold for these values is yet to be determined (Ranson et al., 2008; Stuelcken et al., 2008; Senington et al.,2018).

Finite element analysis and 3D simulators have been used to model the response of the spine to different loading patterns (Chosa et al., 2004; Bruno et al., 2017). Loading under compression, flexion, extension, and rotation all showed the location of stress principally in the pars interarticularis (Chosa et al 2004). The stress at L5 pars interarticularis was highest under compression with extension followed by compression with rotation, flexion, and lateral bending. Bruno et al. (2017) stated that the highest compressive loads experienced at L5 occur during the action of flexion with loading. Ranson et al. (2008) emphasised that during the bowling action fast bowlers subject the lumbar spine to similar movements and forces to those modelled by Chosa et al. (2004).

Despite hyperlordosis of the lumbar spine being associated with lumbar stress fractures (Been et al., 2011) and disc height loss being an indicator of spinal load (Dowzer et al., 1998), no detailed analysis of spinal morphology or shrinkage has ever been included in the analysis of intrinsic risk factors for fast bowling. As long ago as 1992, Elliott and colleagues noted that bowlers had slight lateral curvature of the spine and eight of the 20 bowlers with abnormal radiological features had marked lumbar lordosis (Elliott et al., 1992). Ranson et al. (2007) also stated that there was a need to investigate imaging modalities as a way of establishing the relationship between acute intervertebral disc changes and lumbar stress injury.

1.3.2 Front leg parameters

Lumbar stress fracture has been associated with an extended knee (167° ± 9°) at FFI compared to the non-injured bowlers (154° ± 13°) despite this difference not being statistically significant (Portus et al 2004). In contrast, Olivier et al. (2015) found that of 17 fast bowlers analysed pre- and post-season, those with no injury (n=8) at the end of the season had a similar knee angle at FFI (157° ± 12°) to the injured cohort (9) (161° ± 8°). Portus et al. (2004) and Worthington et al. (2013) confirmed that flexion and then extension of the knee, or having the knee already extended in the early part of FFI increased ground reaction force (GRF). Thus, the relationship with GRF may help in identifying the aetiology of spinal injury.

A review of vertical and horizontal components of GRF during bowling revealed a range of 3.5 – 7.3 body weight and 1.4 – 4.5 body weight respectively at FFI (Sennington et al., 2018). Although it is noted in the literature that GRF represents the considerable load that fast bowlers are required to absorb, particularly at FFI, no study has reported a relationship with either bowling action or back injury. Whilst GRF measured in the single delivery does not appear to be related to the aetiology of injury, the volume and rate of the application of these forces has merited attention (Sennington et al., 2018).

Bayne et al. (2015) showed statistically significant differences in front leg hip flexion angle at FFI (injured 46° ± 6°, non-injured 51° ± 6°), thereby supporting previous research that showed an association between a more extended front hip and low back injury (Foster et at., 1989; Elliott et al., 1992; Portus et al., 2004). Worthington and colleagues reported the plant angle as the angle between the vertical line from the centre of the hip joint to a line joining the centre of the ankle joint to the hip joint. A larger plant angle (i.e., a more flexed hip) and a heel strike technique at FFI were associated with lower peak GRF and a longer time to peak GRF (Worthington et al., 2013). Alway et al. (2019) reported that increased rear hip and knee angles at BFI were associated with increased risk of lumbar injury. Interestingly this study used logistic regression analysis to help predict injury. This form of statistical analysis using an algorithm for binary prediction (i.e.yes/no) of injury, has been suggested as a new approach to investigate injury risk analysis (Ruddy et al., 2019).

1.3.3 Workload

The number of balls bowled (deliveries) has been used as a measure of external workload for fast bowlers (Perrett et al., 2020). Research has proposed a dual workload threshold for injury risk where both under and over bowling are implicated (Alway et al., 2019; Perret et al., 2020; Tysoe et al., 2020), with a minimum of 123-188 deliveries per week suggested to increase resilience to injury (Dennis et al. 2003). Furthermore, Alway et al. (2019) reported that bowlers who exceeded 300 deliveries per week compared to those not achieving this total, were 1.7 times more likely to sustain a lumbar stress fracture injury (relative risk (RR) 1.77 95% CI 1.05-2.98). Similarly, Orchard et al. (2009) found that those bowlers bowling 234 deliveries per week compared to 193 were 3.18 times more likely to sustain the same injury (RR 3.18 95% CI 1.72-3.63).

The Acute Chronic Workload Ratio (ACWR) has compared the relationship of workloads over various time periods in relation to injury risk in fast bowlers (Hulin et al., 2014; Sims et al., 2017; Warren et al., 2018; Tysoe et al., 2020). ACWR is calculated by dividing the weekly bowling workload in balls delivered (acute) by a 28-day average (chronic) (Hulin et al., 2014). An ACWR of more than 1.42 (Warren et al., 2018) and 2.00 (Hulin et al. 2014) has been associated with relative risks of lumbar injury of 1.6 (95% CI 1.06-2.59 – compared with an ACWR of 0.87) and 4.5 (95% CI 3.43-5.90 – compared with an ACWR 0.5-0.99) respectively. Both groups reported that a higher chronic workload over 28 days (>83 deliveries) served to attenuate the risk, supporting the work of Dennis et al. (2003), that there is a need to maintain a bowling load in order to enhance injury resilience. Other ACWR timeframes have been postulated with a nine-day acute and 21-day chronic comparison resulting the best fit for the multivariable model proposed by Tysoe et al. (2020). The same authors also advocated using 'differential load', representing the smoothed week-to-week rate change in workload, to measure injury risk. A twice-the-standard-deviation increase in seven-day differential load (22 overs - RR 2.47 90% CI 1.27-4.8), 42-day chronic load (17.5 overs/week - RR 6.77 90% CI 2.15-21.33) and a high 9-day acute load (45.5 overs/week – RR 133.33 90% CI 25.26-703.81) were all independently associated with an increased risk of injury (Tysoe et al., 2020).

In contrast to the studies above, Sims et al. (2017) did not support the use of ACWR as they found no relationship between injury and spikes in workload in a prospective study of 65 fast bowlers with 12 lumbar fractures. Recent research has also criticised the use of ACWR highlighting limitations of using ratios to calculate injury risk as they are prone to mathematical artefacts influencing the results (Impellizerri et al., 2020; Wang et al., 2020). A key artefact lies in scaling a value to another value, with the assumption of linearity in the relationship between the two variables. If this is not the case between variables, then the ratio under/overestimates injury risk, and most likely, not consistently (Impellizerri et al., 2020). Bayne et al. (2015) also found that bowling workload was not an injury risk factor in adolescent fast bowlers, although the authors did not use ACWR in their analysis. The contradictory nature of different studies that have investigated links between workload and injury to fast bowlers may be due to the limitations they have in self-reporting their workloads.

High chronic workload and cumulative loading over time have also been implicated in spinal injury (Orchard et al., 2015; Sims et al., 2017; Warren et al., 2018). Bowling workload exceeding 900 deliveries in 90 days increased injury risk significantly (Orchard et al., 2015). However, despite statistically significant differences in 28- and 90-day workloads between non-injured and injured fast bowlers, neither was associated with a significant risk of lumbar stress fracture (Alway et al., 2019). Interestingly, a career bowling workload of over 12 000 overs appears to have a protective effect (Orchard et al 2015), although this could also be a selection effect in that to achieve such a career level you have to have avoided injury. The dilemma is that fast bowlers must bowl to allow the body's tissues to adapt to the forces placed on them, but too much may tip the balance in favour of microdamage to biological structures and their potential failure. The time between bowling events is important to allow recovery, but also to maintain fitness to bowl. An average of less than two days (RR 2.4; 95 % CI 1.6–3.5) (Dennis et al., 2003), or greater than five days (RR 1.8; 95 % CI 1.1–2.9) (Sims et al., 2017) between bowling sessions has been shown to increase the risk of injury.

Research using four- and five-day matches has also shown a significantly increased risk of injury to bowlers delivering more than 50 overs in a single game (Orchard et al., 2009; Orchard et al. 2015). Dennis et al. (2003) reported that bowling second in a multi-day match also increased the risk of injury, indicating the potential effect of fatigue on the risk. However, no research has investigated the density of bowling activity within a match in relation to injury such as the number of overs delivered within a spell of bowling, the number of spells or the rest between spells. With the growth in different forms of the game (five-day Test matches, four-day domestic competitions, one-day 50 over and 20 over formats) research has also looked at injury risk across the season. Alway et al. (2019) highlighted an increase of lumbar stress fracture risk in multi-day formats in mid (July) and late season (September) in English first class cricket. This could be due to the reduced bowler workload during the mid-season 20 over competition needed to maintain injury resistance.

Although workload has been measured in relation to the volume of deliveries bowled, intensity of the delivery has only recently been studied. McNamara et al. (2017) used microtechnology to measure the intensity of bowling by investigating the correlation between the PlayerLoad™ metric (MinimaX S4, Catapult Innovations, Melbourne, Australia) and ball velocity. A strong association was reported between the two variables highlighting that the growth of microtechnology and GPS technology (housing accelerometers, magnetometers, and gyroscopes) allows bowling workload and the intensity of a delivery to be captured during playing and training and related to injury risk (McNamara et al., 2017).

The total physical demands of playing in matches lasting from four hours to five days and associated fatigue have received little attention. Noakes & Durandt (2000) estimated that elite cricketers could play more than 100 days in a year, which has increased dramatically since the advent of 20 over cricket in 2005 (Orchard et al., 2015). Utilising GPS units Peterson and colleagues showed that fast bowlers covered approximately 22 km in a single day of a multi-day game, 13 km in a one-day format and 5.5 km in a 20 over game. Importantly fast bowlers had a greater number of high intensity events over 14.4 $km \cdot h^{-1}$ compared to other player types (Peterson et al., 2009; Peterson et al., 2010; Peterson et al., 2011). Despite this research, indicators of fatigue such as blood lactate, heart rate, core temperature, pH, glucose, and markers of muscle damage (creatine kinase, C-reactive protein) in training and match play indicate that bowlers are well prepared for individual bowling sessions and for more than one bowling spell in a session (Duffield et al., 2009; Lombard et al., 2012; McNamara et al., 2013; Maunder et al., 2017). The combination of bowling workload and additional physical demands within the game require further investigation.

1.3.4 Musculoskeletal parameters

Cricket researchers have used a battery of musculoskeletal screening and fitness tests in their investigations, with several being linked to injury risk. Muscles of the trunk have been shown to play an important role in stabilising the lumbar spine during bowling, with the erector spinae helping to control spinal flexion during the delivery stride and follow through (Cholewicki & VanVliet, 2002; Bayne et al., 2016). The association between hamstring tightness and lumbar lordosis in the predisposition to lower back injury in football has been described by Bruckner et al. (2013). Research with fast bowlers has shown a link between poor hamstring flexibility and intervertebral disc abnormalities in fast bowlers (Elliott et al., 1992). Further research within this population has demonstrated that poor test scores in the single leg decline test (Sims et al., 2010), lumbo-pelvic stability, hip internal rotation (Bayne et al., 2016) and ankle dorsiflexion (Olivier et al., 2015) were related to low back injury.

Muscle asymmetry within the trunk has provided conflicting evidence in relation to injury to fast bowlers. Engstrom et al (2007) found that bowler's asymmetry in the Quadratus Lumborum (QL), consisting of a 25% larger muscle mass on the bowling side was associated with lesions to L4, which the authors theorised could lead to greater shear forces on the pars interarticularis. In contrast other research has found larger asymmetrical QL differences in non- injured bowlers (20.2%) than in injured bowlers (9.1%) advocating the protective nature of QL asymmetry (de Visser et al., 2007; Ranson et al., 2008; Kountouris et al., 2012). Moreover, Johnson et al. (2012) suggested that developing a larger QL on the bowling side may be the result of coping with greater lumbo-pelvic lateral flexion during bowling and was thus a symptom rather than a cause of potential injury.

Bone mineral density (BMD) has also been a focus of research into lumbar stress fractures in fast bowlers (Mickelsfield et al., 2012; Lees et al., 2016; Alway et al., 2019). Significantly greater lumbar spine BMD has been found in bowlers compared to physically active controls and other playing positions in cricket (Mickelsfield et al., 2012; Alway et al., 2019). Using Dual X-ray absorptiometry (DXA) has shown greater BMD contralateral to the bowling arm from L3 to L4, which is the most common site for a stress fracture (Alway et al., 2019). Furthermore, fast bowlers who had a lumbar stress fracture had slightly lower, but non-significant, bilateral BMD in the lumbar vertebrae compared to those who never suffered a fracture Alway et al., 2019). More research is needed to ascertain thresholds for BMD associated with increased injury resistance.

1.4 Spinal curvature

1.4.1 Anatomy

The spinal column consists of 33 vertebrae, arranged in five regions (see Figure 1.10). The cervical, thoracic, and lumbar regions consist of vertebrae that are moveable with the sacrum (S1) and coccyx being fused in adults. The 24 moveable vertebrae normally consist of seven cervical (C1-C7) in the neck or cervical region, twelve thoracic (T1 – T12) connected with the ribs and five lumbar (L1-L5) in the lower back (McGill 2015). Care must be taken when assuming the typical distribution of vertebrae as Paik et al. (2013) reported that from a review of 8280 patients who underwent medical imaging of the lumbar spine, 2.6% and 8.2% displayed four and six lumbar vertebrae, respectively. The vertebrae are connected by resilient intervertebral discs and in conjunction with the vertebrae function to support the trunk, allow movement, locomotion and protect the spinal cord (Middleditch & Oliver, 2005). The vertebrae of the spine are a series of movable joints and when two vertebrae are linked, they are referred to as a motion segment (McGill 2015). One motion segment comprises three joints, one formed from two vertebral bodies with an intervertebral disc in between and two facet joints created by the articulation of the superior and inferior articular processes (Bogduk, 2005). As humans are bipedal the evolutionary development of the S shape of the spine (Figure 2) allows weight bearing and shock absorption to be transmitted through the curves of the vertebral column (Harris & Ranson, 2011).

A typical vertebra is composed of two sections, a body lying anteriorly, and a vertebral arch positioned posteriorly (see Figure 1.11). The vertebrae of different regions vary according to their function (Harris & Ranson, 2011). The cervical vertebrae provide support and movement for the skull with the intervertebral discs below C2 allowing general flexion, extension, lateral flexion, and rotation of the neck (McGill, 2015). The thoracic vertebrae show an increase in size further down the column and the horizontal orientation of the facet joints in the mid-thoracic region allows for rotation, but other movements are restricted by the presence of the ribs (Harris & Ranson 2011).

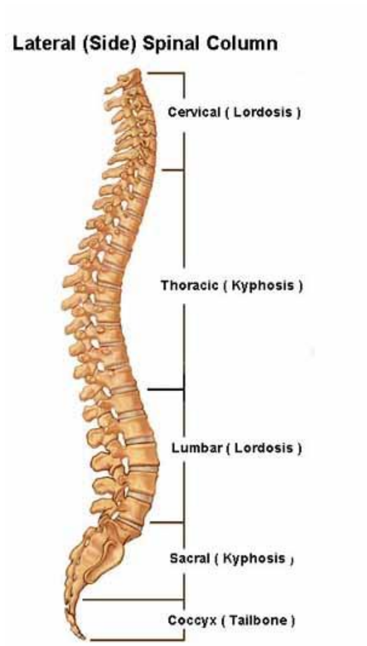


Figure 1.10 - Lateral view of the areas of the spine that give the column its ‘S’ shape. The cervical and lumbar vertebrae concave anteriorly (lordosis) whereas the thoracic and sacral regions concave posteriorly (kyphosis) (from Bridwell & Dodds, 2020)

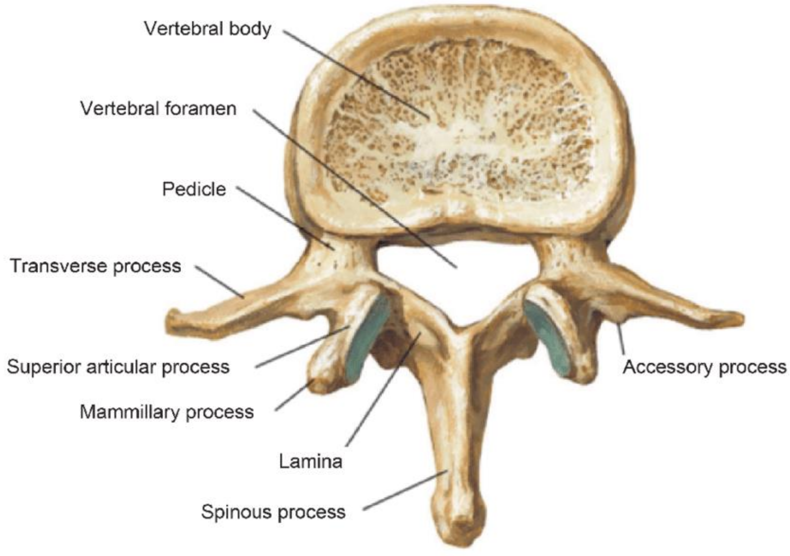


Figure 1.11 – Lumbar Vertebra including vertebral body and neural arch (adapted from Bijendra et al., 2018)

Typical lumbar vertebrae have a large body that is kidney shaped when viewed superiorly and are designed for weight bearing purposes, to accommodate axial compression (see Figure 1.11). The design of the body, with a shell of cortical bone and a cancellous cavity of vertically and horizontally arranged trabeculae, confers the added advantage of stability for dynamic load bearing (Bogduk & Twomey, 1987). The posterior elements of the vertebrae included in the lumbar region are referred to as the vertebral or neural arch, which comprises two pedicles and two laminae supporting two transverse processes, one spinous process and four articular processes (two superior facets and two inferior facets that comprise the facet or zygapophyseal joints) (McGill, 2015). The orientation of the facet joints becomes increasingly vertical in the lumbar region, which helps to prevent sliding of adjacent vertebrae and resists rotation that occurs during the bowling action and that may contribute to the risk of lumbar injury (Ranson et al., 2008).

The pars interarticularis, which lies at the junction of the vertical lamina and horizontal pedicle, bear 40% of the loads on the facet joints at L4/L5 and L5/S1 (Vandlen et al., 2012). Such a high load, particularly with increasing lumbar lordosis, makes this region more vulnerable to stress fracture (Adams et al., 1980; Adams & Hutton, 1980). A lordotic increase of 2° from a neutral position results in an elevated compression force of between 1% and 16% through the facet joints (Adams & Hutton 1980).

1.4.2 Lumbar lordosis

The concave posterior curve of the lumbar spine offers some movement and flexibility through sagittal extension and flexion (see Figure 1.12). Wedging of the intervertebral discs and vertebral bodies, with the anterior parts longer than the posterior, contributes to the lordotic angle (Been & Kalichman, 2014). Up to 40% of the lumbar lordosis can be accounted for by the L4/L5 segment and a more horizontal orientation of facets joints correlate with increased lumbar lordosis (Been et al., 2007; Been et al., 2010). Quantitative evaluation of spinal curvature has been highlighted as essential for monitoring progression and treatment of spinal deformities and for planning surgical interventions (Vrtovec et al., 2009). The clinical and functional importance of lordosis has been reported in the literature (Troup 1976; Adams, et al., 1999; Chen & Wei, 2009) with typical sagittal lordotic angles ranging from 49° - 61° in erect standing (Jackson & McManus, 1994; Lord et al.,1997) and a normal range defined as being between 30° – 80° (Been & Kalichman, 2014) (see Figure 12). Within sport, studies measuring spinal curvature have used narrower ranges with normal lordosis between 20° - 40°, hyperlordosis greater than 40°, and hypolordosis less than 20° (Lopez- Minarro et al., 2010; Lopez-Minarro et al., 2012; Muyor et al., 2013). Been & Kalichman (2014) stated that because the normative ranges for lordosis are so high (30°-80°), determining the optimal angle for health is difficult and more studies are required to investigate the association of lordosis with sporting activity. There may also be a need to further narrow the classification down to ranges that typically occur in particular sports as well as playing positions, such as fast bowlers in cricket to ascertain the importance of specific lordotic angles.

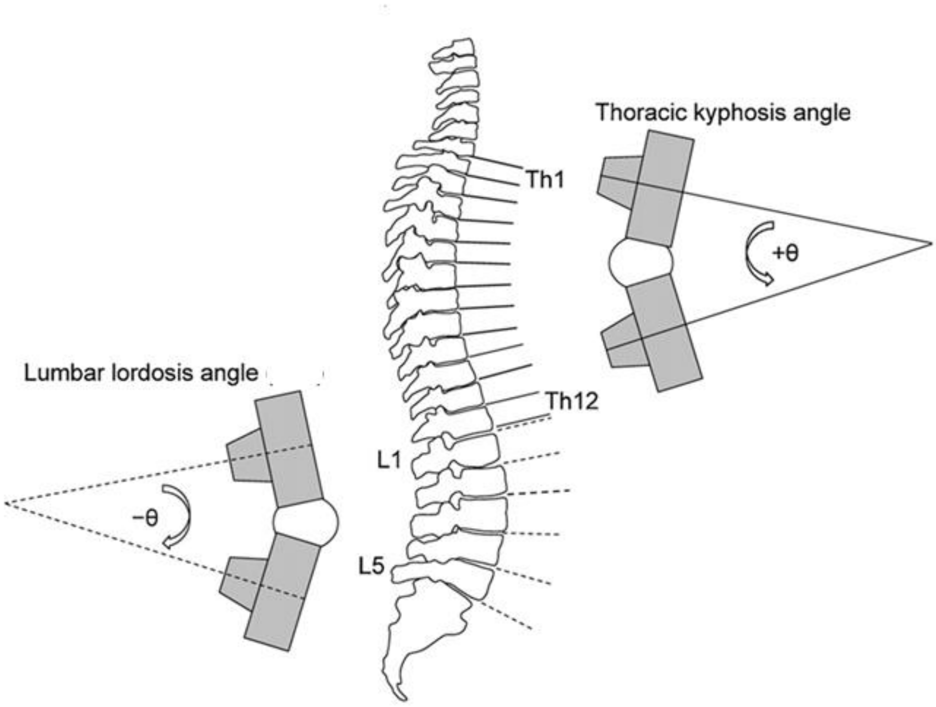


Figure 1.12 - Thoracic and lordotic curvature angle methodology using the mid-line of the vertebral body (from Miyazaki et al., 2013).

1.4.3 Lumbar curvature and injury

Research has shown that a greater lordortic angle may be a risk factor for developing a unilateral lumbar stress fracture (spondylolysis) and bi-lateral fracture (spondylolisthesis) (Berlemann et al., 1999; Been et al., 2009; Labelle et al., 2009; Kalichmann et al., 2011; Been et al., 2014). It has been postulated that increasing lordosis leads to a greater shear force concentrating on the pars interarticularis (Been et al., 2011). However, only limited research has been conducted in sport in relation to the association between injury and curvature of the spine. Alricsson & Werner (2006) found no significant difference in lumbar lordotic angles over five years between skiers who experienced back pain and those who did not. Hecimovich & Stomski (2016) also retrospectively compared lumbar sagittal curvature in a group of 59 (male = 33, female = 26) junior fast bowlers (14 ± 3 years) between those with a history of low back injury and asymptomatic individuals. No statistically significant difference was found between the lordosis of males and females but the group with a previous injury had significantly more curvature (42.53° ±9.10°) than those with no injury history (30.33° ±8.36°; $p<0.01$). Unfortunately, no details were given on the type and severity of injury and the study relied on the accuracy of the players' own recollection of previous injury. These findings highlight the need to use more sophisticated injury reporting when investigating curvature as a possible risk factor for fast bowling injury.

1.4.4 Measuring curvature

The accepted gold standard for measuring sagittal spinal curvature is the lateral radiograph (Hwang et al., 2010; Barrett et al., 2013). Investigations in the medical imaging literature reveal that there are up to 14 methods of measuring lumbar curvature of the spine using 2D radiographic images (Vrtovec et al., 2009). These include angles from the top of L1 to the top of the sacrum (S1), from the top of L2 to the top of S1, from the top of L2 to the bottom of L5, and from the bisect of the disc at L1-L2 to the bisect at L5-S1 (Bogduk, 2005). The variety of approaches make it difficult for comparisons to be made between studies and indicate the likelihood of flaws in published classifications.

The Cobb method has been used extensively to calculate curvatures in the frontal and sagittal planes in the clinical setting (Hwang et al., 2010). The Cobb angle recorded from this method, measured from lateral radiographs, is calculated as that between the superior endplate of L1 and the superior endplate of S1, or the superior endplate of L1 and the inferior endplate of L5 (Hwang et al 2010). Mac-Thiong et al. (2003) noted that lumbar lordosis measured using the Cobb angle can be affected by the deformity in the coronal plane and sagittal alignment of the pelvis, whilst Harrison et al. (2001) indicated that it may be influenced by vertebral end plate geometry. One of the limitations of all 2D measurement devices is their inadequate representation of the complex 3D anatomical structure of the spine in either a frontal or sagittal 2D image (Vrtovec et al 2009). Other problems associated with radiographic methods (X-ray, Computed Tomography) include the dangers of exposure to ionising radiation. This makes the use of such methods with asymptomatic participants ethically questionable and may be the reason for the paucity of studies in sport using such approaches. MRI offers a 3D solution, but cost is a major limiting factor in research using this mode of image acquisition (Barrett et al., 2014). In response to these issues many researchers have utilised a variety of non-invasive devices (Barrett et al., 2014).

1.4.5 Non-radiographic methods for measuring curvature

The means for measuring curvature of the spine without exposing the participant to radiation doses can be categorised into skin-surface devices and technical-based equipment (Barrett et al., 2013). Skin-surface tools include Debrunner's kyphometer (Nillson et al., 1993; Alricsson & Werner, 2006; Todd et al., 2015), the arcometer (Chaise et al., 2011), goniometers (Gravina et al., 2012), the spinal wheel (Sheeran et al., 2010), the flexicurve (Hecimovich & Stomski, 2016) and the Spinal Mouse (Lopez-Minarro et al., 2011; Muyor et al., 2013 a; Muyor et al., 2013 b; Lopez- Minarro et al., 2017). Technical-based equipment consists of the use of computer posturography (Grabara. 2012) and 3D Ultrasound (Folsch et al., 2012; Prushansky et al., 2013). By Currier's criteria (1990), these devices demonstrate a range of poor to high between-day and within-day, inter-rater and intra-rater reliability for measuring lumbar lordosis (ICC of 0.90-0.99 = high reliability, 0.8-0.89 = good reliability, 0.70-0.79 = fair reliability and <0.69 = poor reliability). Hecimovich & Stomski (2016) used a flexicurve to measure lumbar lordosis only in junior level fast bowlers and reported fair within-day intra-rater reliability (ICC 0.7).

The Spinal Mouse is a hand-held computer based electromechanical device that measures spinal curvature in the sagittal and frontal planes. It has been used in research on tennis (Muyor et al., 2013 a), canoeing (Lopez-Minarro et al., 2011), kayaking (Lopez- Minarro et al., 2017) and cycling (Muyor et al., 2013 b). High within day intra-rater reliability for the device has been reported for measuring upright lumbar sagittal curvature (ICC 0.9 – 0.985) (Keller et al., 2000; Manion et al., 2004; Kellis et al., 2008; Topalidou et al., 2014; Roghani et al., 2017). However, between-day inter-rater reliability has ranged from poor to high (ICC 0.61 – 0.96), with a measurement error between 0.72° – 13.18° (Kellis et al., 2008). Two studies have demonstrated lower measurement error (SEM 0.39° - 1.7°) for lumbar lordosis due possibly to the use of a more precise standardized protocol and more experienced testers (Topalidou et al., 2014; Roghani et al., 2017). Researchers have highlighted the following advantages of using the Spinal Mouse; speed of measurement, automation of calculations, relative cost, and the ability to monitor and record continuously without exposure to ionising radiation (Keller et al., 2000; Manion et al., 2004; Kellis et al., 2008; Topalidou et al., 2014; Roghani et al., 2017).

The Spinal Mouse has been compared to radiographic measurements in two investigations. Ripani et al. (2008) reported weak correlations with radiographic analysis and none for 11 of the 17 segmental measures taken in the frontal plane, concluding that the device was not valid for measurements in this plane. Conversely, Livanelioglu et al. (2015) reported strong or very strong associations between frontal plane measurements using the radiographic Cobb angle and the Spinal Mouse. This may have been due to measurements being taken by more experienced raters. Unfortunately, neither author measured global angles for lordosis or kyphosis in the sagittal plane, and no studies have measured the validity of the Spinal Mouse in this plane.

1.5 Spinal shrinkage

1.5.1 Anatomy of intervertebral discs

The intervertebral discs provide the strongest attachment between the bodies of the vertebrae (McGill, 2015) and vary in size and thickness in different regions with those in the lumbar region being thickest (Adams et al., 2006). The same authors state that the structure of the discs must be pliable enough to allow for small movements whilst maintaining appropriate stiffness to cope with compression loads. The height of a typical lumbar disc has been reported at 10 mm (Adams et al., 2006) and a 1 mm loss in disc height has been shown to lead to a four-fold increase in forces through the facet joints (Adams & Hutton, 1980). Dunlop et al. (1984) reported that this loss in height coupled with an increase in lordotic angle, especially in extension, led to markedly increased forces that could contribute to damage of the facet joints. As previously mentioned, wedging of the intervertebral discs, with the anterior parts thicker than the posterior, contributes to the lordotic angle of the lumbar region. Thus, measuring alterations in disc height either directly or indirectly is important when trying to understand load and potential injury to the lumbar spine (Been & Kalichman, 2014).

An intervertebral disc is composed of an annulus fibrosus (AF), which surrounds the internal gelatinous nucleus pulposus (NP), with both structures sandwiched between a pair of cartilaginous vertebral end plates (McGill 2007). The AF consists of concentric sheets of collagen fibres named lamellae (see Figure 1.13) which display alternating orientation in up to 20 successive layers aligned to withstand multidirectional forces and provide tensile strength (Adams et al., 2006). The lamellae have been shown to be thinner and less numerous posteriorly than they are anteriorly or laterally. Gower and Pedrini (1969) stated that the AF consisted of 60% to 70% water, with 50% to 60% and 20% of the remaining dry matter coming from collagen and proteoglycan cells, respectively. The hydrophilic nature of the proteoglycan molecules has been reported to give the disc a high osmotic pressure, which maintains its fluid content (Middleditch & Oliver, 2005). With increasing age proteoglycan and, thus, water content has been shown to decline (Gower & Pedrini, 1969).

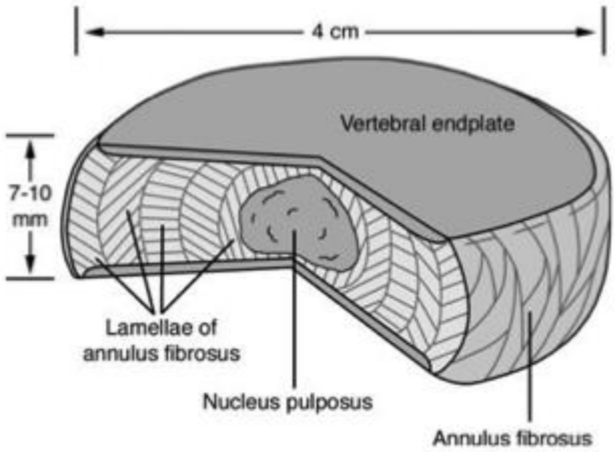


Figure 1.13 Arrangement of the annulus fibrosus lamellae in vertebral disc (adapted from Tomaszewski et al., 2015)

The semifluid NP is composed of 70% - 90% water with proteoglycan constituting 65% of the dry weight and collagen compromising 15% - 25% (Gower & Pedrini, 1969). The nucleus forms the central core of the disc and lies posteriorly in the cervical and lumbar regions. Its main function is as a shock absorber for axial forces and it has been proposed to act like a semifluid ball- bearing during flexion, extension, rotation, and lateral flexion (Bogduk and Twomey, 1987). Intervertebral discs play an essential role in fast bowling where they must absorb forces as the bowler's trunk is hyperextended, laterally flexed, rotated and flexed (Burnett et al., 1995).

1.5.2 Stature loss and spinal shrinkage

Early research by De Puky (1935) showed that in a sample of 1216 males and females ranging from five to ninety years of age, average stature was reduced by 1% during the activities of a day with diurnal variation for children being 2% and, for older adults, 0.5% of height. Later research confirmed the circadian nature of stature loss to be approximately 1% of body height (20mm) during the day with subsequent recovery during lying down at night (Eklund & Corlett, 1984; Reilly et al., 1984; Tyrrell et al., 1984). Reilly et al. (1984) also stated that a rapid loss in stature occurred in the first hour after rising, accounting for up to 50% of the diurnal loss under constant loading conditions with a slowing in the rate of loss throughout the remainder of the day.

The deformation of body tissue under load over time is defined as 'creep', and usually involves expulsion of water from the NP (Adams et al., 2006). Kramer et al. (1985) noted that the opposite occurred when a load was removed involving an influx of water into the disc that contributed to the increase in height. Examination of the creep response has shown the initial displacement of the disc upon loading to be caused by mechanical deformation of the AF through sideways expansion (bulging) and vertical changes to the vertebral endplate, while longer term displacements were due to fluid flow from the NP and AP (Van Dieen & Toussaint, 1993; MacLean et al., 2007; van der Veen et al., 2008).

1.5.3 Spinal shrinkage as a measure of spinal load

Direct measurements of disc height loss have included *in-vitro* analysis of cadavers (Senck et al., 2019) and animal spines (Nikkhoo et al., 2015) as well as MRI (Kimura et al., 2001; Lewis & Fowler, 2009), X-ray (Pooni et al., 1986), ultrasound (Sobczak et al., 2016) and finite element analysis (FEA) (Schmidt et al., 2007). Stadiometry has been used extensively in clinical settings as an indirect measure of disc height loss, with total stature loss (1.8 - 4.2mm) corresponding to increased loads on patients' shoulders (Tyrrell et al., 1985; Corlett & Eklund 1986; Altoff et al., 1992). Weight training and circuit training have consistently shown spinal shrinkage ranging from 4.3 ±0.3 mm to 5.4 ±0.3 mm (Leatt et al., 1986; Wilby et al., 1987; Bourne & Reilly 1991; Garbutt et al., 1994) Shallow water running for 30 minutes resulted in greater shrinkage (5.51 ±2.18 mm) than treadmill (4.59 ±1.48 mm) and deep water running (2.92 ±1.7 mm) (Dowzer et al.,1998), due possibly to greater rotational and torsional stress whilst running in water.

1.5.4 Recovery of spinal height

Reilly et al. (1984) demonstrated that restoration of height lost during the day occurred during the night with 71% of recovery in the first half of the night's sleep. Studies measuring response to load have tried to replicate this recovery using a variety of methods, including horizontal lying (Eklund and Corlett 1984), side lying (Rodacki et al., 2003), adopting the Fowler position (Tyrrell et al., 1985; Rodacki et al., 2003), gravity inversion (Leatt et al., 1986; Boocock et al., 1990), spinal hyperextension (Magnusson & Pope, 1996; Owens et al., 2009; Munster et al., 2018), 110° supported sitting (Magnusson & Hansson, 1994), and abdominal crunch exercises (Rodacki et al., 2008). Healey et al. (2005) reported that whilst no significant difference occurred in shrinkage after loading in participants with and without low back pain, those with pain experienced significantly reduced recovery in a variety of unloaded positions.

1.5.5 Spinal shrinkage in cricket

Eklund & Corlett (1987) reported that spinal shrinkage is affected by both load and its temporal pattern, and Koeller et al. (1984) showed a greater rate of deformation with intermittent compared to continuous loading of similar magnitude. The dynamic nature of loading at intervals has also been tested by Tyrrell et al (1985), who found that it caused significantly greater shrinkage when compared to a static protocol. As fast bowling has been shown to involve the bowler typically experiencing peak vertical forces at front foot impact of between four- and six-times body weight (e.g. Foster et al., 1989), repeated six times an over, with the potential for many overs per day, it seems reasonable to categorize this as dynamic loading.

Reilly & Chana (1994) compared spinal shrinkage in 18 young fast bowlers delivering 60 balls (bowling trials) with the same group only running into bowl (run-up trials). The bowling trials were repeated after unloading through body inversion on a tilted table for five minutes at 50° to the vertical. Bowling trials resulted in shrinkage of 2.30 ±1.58 mm whilst the run-up only trials caused a loss of 0.29 mm. The loading during delivery was assumed to be the cause of additional shrinkage. Gravity inversion increased stature by 2.66 mm and subsequent bowling resulted in 2.68 ±1.9 mm shrinkage, highlighting the protective nature of the recovery method. The ecological validity of the protocol could be criticized as bowlers did not rest between each over and the 20-minute standing period prior to measurement may not be considered a suitable unloading protocol.

Barry (2007) found shrinkage during eight overs of bowling in nine male fast bowlers to be similar in those with a mixed action (3.41 ±0.85 mm) and the front/side on techniques (4.14 ± 1.44 mm). Reilly & Chana (1994) and Barry (2007) both found shrinkage to have a linear nature with the overs bowled, thus indicating that the intervertebral discs may have the capacity for further creep activity. Barry (2007) allowed more relevant breaks between overs and the overall volume of deliveries (thus load) was lower compared to Reilly & Chana (1994) (48 v 60 deliveries). Despite this, greater shrinkage was found by Barry (2007), which may be due to the 40 minutes standing prior to bowling, as advocated by Reilly & Chana (1994) or that different and individually modified versions of the stadiometer first proposed by Eklund & Corlett (1984) were used. Moreover, Barry (2007) reported that neither peak vertical nor peak horizontal forces, normalized to body weight, at FFI or time to reach peak force were related to shrinkage rates.

1.5.6 Stadiometry

The indirect measurement of spinal shrinkage *in vivo* is based on changes in stature. Eklund & Corlett (1984) developed a stadiometer that became the blueprint for other researchers to adapt and modify as they measured changes in body height to within 0.1 mm. Such stadiometers comprise an inclined frame of between 5-15° to the vertical, allowing the participant to adopt a relaxed posture, whilst using support switches or postural rods to maintain the individualized curvature of the spine (Reilly et al., 1984; Boocock et al., 1990). Having a reliable individualized curvature of the spine is crucial to the validity of the measurements as Goode & Theodore (1983) reported voluntary variations of spinal curvature could lead to changes in stature of up to 36 mm. Weight distribution between heels and forefeet, the phase of the respiratory cycle, and control of the head angle were also important in achieving valid and reliable measures (Reilly et al., 1984).

1.5.7 Reliability and validity of stadiometry

The criterion used for determining adequate reliability in a custom-built stadiometer is ten successive participant measurements with a standard deviation (SD) ≤0.5 mm (Tyrrell et al., 1985). This represented a target that was realistic whilst being smaller than normal observed changes in stature (Healey et al., 2005). Participants are often required to attend training on multiple occasions, lasting no more than one hour to attain an appropriate level of reliability (Leatt, 1986; Corlett et al., 1987).

Reliability of stature has involved within-day and between day measurements as well as the same rater and different raters (Leivseth & Drerup 1997; Kanlayanaphotporn et al., 2002; Healey et al., 2005). Leivseth & Drerup (1997) measured shrinkage on two consecutive days and found good reliability with reported mean SDs of 0.51 mm with a standing load. Kanlayanaphotporn et al., (2002) and Healey et al., (2005) reported between-day intra- rater reliability using a custom-built stadiometer, with Standard Error of the Measurement (SEM) ranging from 0.8 mm to 1.9 mm. Recently two commercially available stadiometers from Seca demonstrated good within-day inter-rater and intra-rater reliability (ICC - 0.999; SEM - 1mm) (Baharudin et al., 2017).

MRI has been used as the gold standard for measuring disc height loss (Boos et al., 1996; Park, 1997). Lewis & Fowler (2009) reported a moderate correlation between stature loss measured using a stadiometer and posterior spine length from an MRI ($r = 0.61$, $p=0.02$). The same authors reported difficulties using MRI to measure spine length, first in controlling posture and secondly in obtaining clear images. Within-day intra-rater SEM of 0.4mm for each disc was reported by Lewis & Fowler (2009), thus questioning the role of upright MRI as the gold standard for spinal shrinkage measurements.

Before investigating spinal shrinkage and lumbar lordosis as risk factors in the injury of fast bowlers, investigation of the reliability and validity of stadiometers used in the field is needed. The following chapter addresses this issue and includes the measurement of spinal morphology alterations in response to bowling in amateur bowlers.

Chapter 2 – The acute effect of fast bowling on the morphology of the spine and an examination of the reliability of current measurement devices.

2.1 Introduction

Epidemiological research has shown that, among cricketers, fast bowlers are at greatest risk of injury, with the back being the most common site of injury (Johnson et al., 2012; Arora et al., 2014; Langley et al.,2015; Orchard et al., 2016; Goggins et al., 2020). Analysis of fast bowlers' actions has demonstrated that during the delivery stride the trunk must be hyperextended, laterally flexed, rotated and then flexed while ground reaction forces up to six times the body weight are absorbed (Elliott et al., 1992). The stress resulting from these mechanical loads has resulted in a high prevalence of lumbar disc abnormalities, bone stress reactions and lumbar stress fractures (spondylolysis and spondololithesis) in fast bowlers (Elliott et al., 1992; Elliott et al., 1993; Elliott & Khangure, 2002; Ranson et al., 2005; Crewe et al., 2012; Alway et al., 2019). Ranson et al. (2005) noted that bowlers appear to develop bone problems before disc degeneration and stressed the need to investigate imaging modalities to establish the relationship between acute intervertebral disc (IVD) changes and lumbar stress injury.

Shrinkage, or decrease in stature, has been used as an indirect measure of IVD height loss and as an index of spinal loading in both occupational (Eklund & Corlett, 1987; Stahlhammar et al., 1989; McGill et al., 1996; Van Dieen et al., 1998; Benyon et al., 2000; Kuiper et al., 2004; Healey et al., 2005; van Deursen et al., 2005; Munster et al., 2018) and sporting contexts (Leatt et al., 1986; Wilby et al., 1987; Bourne & Reilly, 1991; Garbutt et al., 1990; Garbutt et al., 1994; Fowler et al., 1997; Dowzer et al., 1998; Reilly & Freeman 2006; Rodaki et al., 2008). Adams & Hutton (1980) demonstrated that any loss of disc height increased the load on the facet (zygapophyseal) joints in cadaver specimens, with a reduction of 1 mm resulting in an increase in load from 4% to 16% when a compressive force of 1 kN was applied. Moreover, an increase in load on the facet joints when the spine laterally flexes is implicated in the aetiology of spondylolysis (Adams et al., 2006), indicating the relevance to fast bowlers of spinal shrinkage as a measure of spinal load. Spinal shrinkage has not been implicated in the aetiology of injuries to fast bowlers, and only two studies have measured shrinkage through stature loss in this population. Reilly and Chana (1994) reported 2.3 ±1.58 mm shrinkage after 30 minutes of bowling, and Barry (2007) demonstrated a mean linear shrinkage of 3.8 ±1.15mm after eight overs of fast bowling in asymptomatic bowlers.

Excessive curvature of the spine along with the narrowing of disc space has also been implicated in a variety of spinal disorders including low back pain, spondylolysis, and disc degeneration (Keller et al., 2005; Kimura et al., 2001). Been & Kalichman (2014) reported a greater lumbar lordotic angle to be a risk factor in developing spondylolysis, as changing lumbar lordosis from the neutral position to a further 2° of lordosis increased the compression force through the facet joints from 1% to 16% (Adams & Hutton 1980). Specifically among junior fast bowlers, Hecimovich and Stomski (2015) found that those reporting low back pain in the previous season had higher levels of lumbar lordosis than those with no injury history (42.53 ± 9.10° v 30.33 ± 8.36° ; $p<0.01$). The paucity of research highlighting the clinical and functional importance of lumbar lordosis in cricket may be due to ethical issues regarding exposure of asymptomatic young bowlers to doses of ionising radiation through x-rays. A variety of skin surface measurement devices including goniometers, inclinometers, and accelerometers provide an alternative solution to this measurement problem (Barrett et al,.2014). The Spinal Mouse (Idiag, Volkerswill, Switzerland) is a hand-held computer based electromechanical device housing an accelerometer that has been used to measure spinal curvature in the sagittal and frontal planes in tennis (Muyor et al., 2013 a), canoeing (Lopez-Minarro et al., 2013), kayaking (López- Miñarro et al., 2017) and cycling (Muyor et al., 2011). The device has never been used in cricket, despite lumbar lordosis being implicated as a risk factor in the aetiology of spondylolysis (Been & Kalichman 2014).

Reliability of devices to measure both stature loss and curvature of the spine should involve good reproducibility of an observed value when the measurement is repeated (Hopkins, 2000). Stability reliability can involve within-day and/or between-day measurements and the same or a different rater (Atkinson & Nevill, 1998). Changes in body height to within 0.1 mm have been measured using a stadiometer developed by Eklund and Corlett (1984) (see Figure 2.1). The criterion for determining adequate within-day reliability of such a custom-built stadiometer is ten successive participant measurements with a standard deviation (SD) ≤0.5 mm (Tyrrell et al., 1985; Leivseth & Drerup 1997). Between-day reliability has been reported as a SEM ranging from 0.8 mm to 1.9 mm (Kanlayanaphotporn et al., 2002; Healey et al., 2005).

The Spinal Mouse has been shown to have good within day reliability when measuring upright lumbar sagittal curvature with ICCs ranging from 0.90 – 0.98 (Keller et al., 2000; Manion et al., 2004; Roghani et al., 2004 Topalidou et al., 2015). However, between-day inter-rater reliability has ranged from poor to high (ICC 0.61 – 0.96) for sagittal lumbar and thoracic measurements in upright standing, flexion, and extension. For the same movements, measurement error has been reported between 0.72° – 13.18° (Kellis et al., 2008), although error has been shown to be reduced (SEM 0.39° - 1.7°) for lumbar lordosis (Topalidou et al., 2014; Roghani et al., 2017). No research on the reliability of stadiometer and the Spinal Mouse within the population of fast bowlers is available.

Aim – To investigate the acute effect of fast bowling on spinal shrinkage and curvature of the spine, including an examination of the reliability of current measurement devices.

Objectives

To ascertain the alterations in spinal shrinkage and curvature after eight overs of fast bowling (Study 1).

To establish the within-day and between-day reliability of Spinal Mouse measurements of lumbar curvature in the sagittal and frontal planes (Study 2).

To determine the within-day and between- day reliability of the custom-built stadiometer measurements of spinal shrinkage (Study 3).

2.2 Methods

2.2.1 Preamble

This chapter consists of three studies. Study 1 measured alterations in spinal shrinkage and curvature after eight overs of fast bowling. The second study focussed on within-day and between-day reliability of the Spinal Mouse measurements of lumbar curvature in the sagittal and frontal planes. Study 3 assessed between-day reliability of the custom-built stadiometer. All studies received ethical approval from the University of Cumbria Research Ethics Committee. Participants were fully briefed about the procedures prior to the commencement of any testing and were given the opportunity to ask any questions after reading the participant information sheets (see Appendix 1). Informed consent was obtained from all participants (see Appendix 2).

2.2.2 Spinal shrinkage (Study 1 and Study 3)

A custom-built stadiometer based on the design of the apparatus used by Eklund and Corlett (1984) was used to measure stature change, following the established method for such a device (Lewis & Fowler 2009). It consisted of a central pillar supported by an aluminium framework, inclined at an angle of 15° to the vertical to encourage the participants to relax during measuring (see Figure 2.1). Postural pads contacted and maintained the prominent curvatures of the spine and head at four anatomical points. These were identified as (1) the most posterior point of the head at the occiput, (2) the deepest point of cervical lordosis, (3) the most prominent point of thoracic kyphosis, and (4) the deepest point of lumbar lordosis. Repeatable head alignment was achieved by having the participant wear spectacle frames with a laser emitter in the arms, that shone vertically on to moveable magnetic plates above the participant. A high-resolution linear variable displacement transducer (LVDT) was lowered until contact with the apex of the participant's head. Changes in electrical current were converted by custom build software to detect variations in vertical displacement to an accuracy of 0.1mm. A sampling rate of 100Hz was used with data collected and stored digitally for later analysis. Participants were without shoes, and their measurements were taken after they had been standing for two minutes to allow any soft tissue changes to stabilise (Foreman & Linge 1989).

2.2.3 Spinal curvature (Study 1 and Study 2)

The handheld Spinal Mouse (ldiag, Volkerswill, Switzerland) was used for all curvature measurements (Figure 2.2). The device includes two rolling wheels that follow the contours of the spinous processes with data points sampled approximately every 1.3 mm via inbuilt accelerometers (Manion et al., 2004; Muyor et al., 2011). The time required to cover the length of the spine was roughly 3 s. With the sampling frequency at 150 Hz, this computed to approximately 420 measurements. The information was relayed via Bluetooth to a personal computer located within 1-2 m of the device.

Figure 2.1 - Lateral view of custom-built stadiometer based on design of Eklund & Corlett (1984) (from Healey et al. (2005).

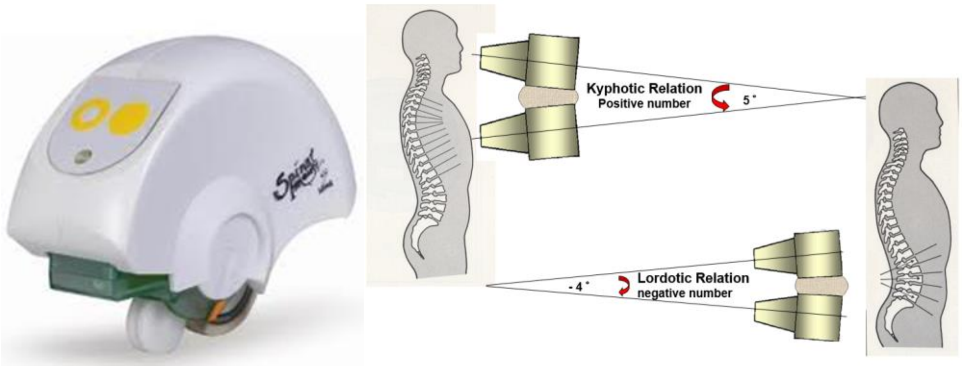


Figure 2.2 - Spinal Mouse and measurement angles. (from Spinal Mouse user manual - https://static1.squarespace.com/static/51763de2e4b0e95e599b4f29/t/52fceaa5e4b01b2bb4f8caba/1392306853736/xUser_Guide_SM_SW_EN_16.10.13.pdf)

Utilising intelligent recursive algorithms, the manufacturer's software converted the data into positions of the vertebral bodies (Manion et al., 2004). Results were reported in degrees with positive values for thoracic curvature and negative for lumbar (Figure 2.2).

Prior to measurement, the spinous process at C7 was palpated and marked on the skin and a second mark was placed at the top of the rima ani (corresponding to S3), (Mannion et al., 2004; López- Miñarro et al., 2010; Post & Leferink 2004). The device was then rolled in a caudal direction in a slow controlled manner between the two marks on the skin. The participants were barefoot for all three measurements, before the mean value was recorded.

Sagittal plane measurements consisted of lumbar lordosis from L1-L5, and thoracic kyphosis from T1-T12, in upright, flexed, and hyperextended positions (see Figure 2.3 a-c). For upright measurements, participants were instructed to remain in a neutral position, focussing on a marker at eye level, with knees extended, feet shoulder width apart and arms hanging by the side.

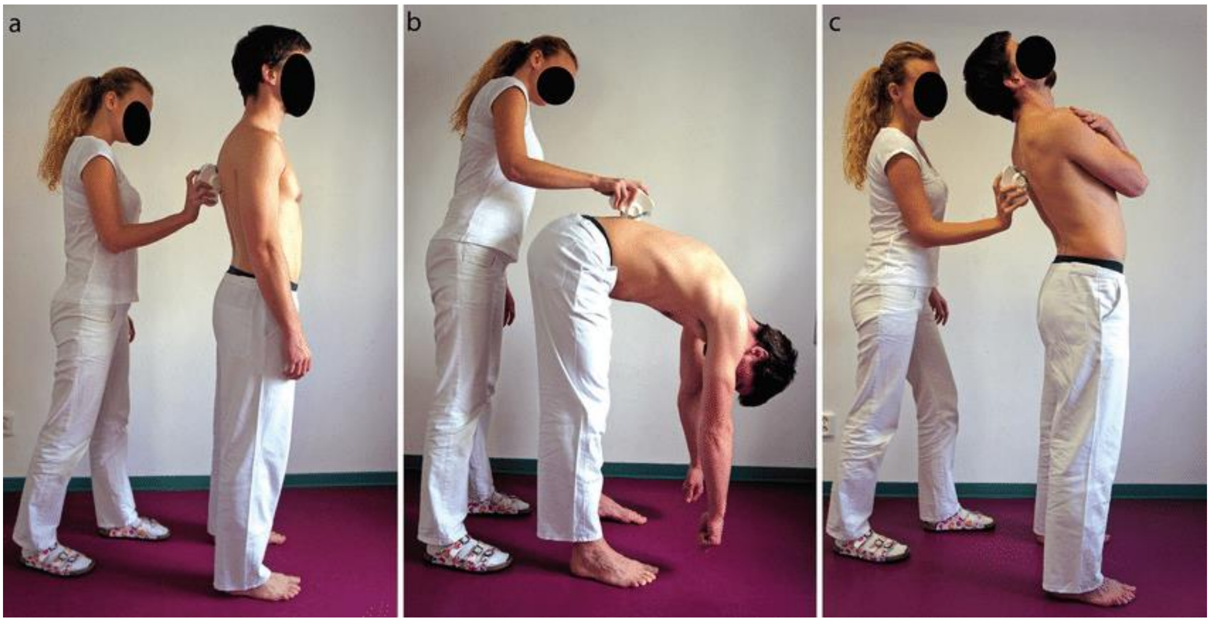


Figure 2.3 - Sagittal upright (a), flexion (b) and extension (c) positions for measuring curvature (from Kapitan et al., 2019)

In maximal flexion the bowlers flexed their trunk in a controlled manner, with straight legs, whilst attempting to curl the head towards the knees. In hyperextension, their hands were placed across the chest with the thighs and hips still. The head was kept in a neutral position while the bowlers hyperextended their trunk as far as was comfortably possible. Participants were asked to move at a controlled speed and hold the end position (flexed and hyperextended) for 3 s to ensure measurements were completed.

After further palpation, additional marks were placed on each of the spinous processes between C7 and L5. Frontal plane measurements for thoracic and lumbar joint angles were then conducted in the upright, left and right lateral flexion positions (Figure 2.4). For lateral flexion, bowlers kept their hands by their sides, sliding the palm down the outside of the appropriate thigh and holding at end range for 3 s. They maintained extended legs and slowly moved laterally (left and right) to a comfortable end range of motion. When measuring the lateral flexion movements, the rater followed the line created by joining the marks made on the spinal processes.

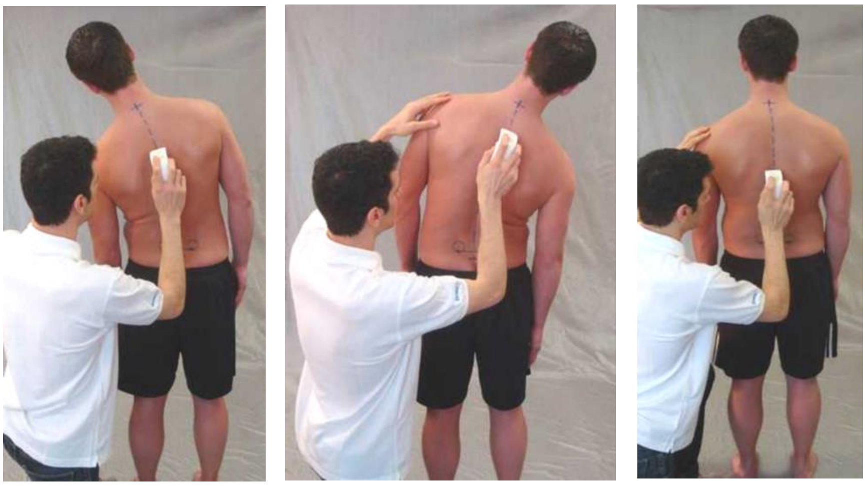


Figure 2.4 – Upright and lateral flexion frontal plane measurements
(from Spinal Mouse user manual
https://static1.squarespace.com/static/51763de2e4b0e95e599b4f29/t/52fceaa5e4b01b2bb4f8caba/1392306853736/xUser_Guide_SM_SW_EN_16.10.13.pdf)

2.2.4 Participants

In Study 1 eleven male fast bowlers (all right arm dominant) aged (mean ± SD) 20.9 ± 1.07 years, mass 75.4 ± 6.03 kg and height 179.9 ± 3.3 cm who self-reported as playing first team adult club cricket in premier leagues in the north west of England were recruited for the study. In Studies 2 and 3 ten male fast bowlers (all right arm dominant) of a similar standard aged 20.8 ± 1.22 years, mass 84.7 ± 15.65 kg and height 179.8 ± 4.6 cm volunteered. All participants had been free from back pain within the previous six months. Bowlers were instructed to refrain from exercise on the day prior to testing and requested to rise from bed at least four hours prior to testing to minimise the effects of circadian variation (Tyrrell et al., 1985).

2.2.5 General protocol

Each bowler's stature and curvature were measured between 11:00-16:00 hrs for the respective studies. They were required to bowl eight overs in Study 1 and six overs in Studies 2 and 3, at approximately one delivery every 28 seconds. Four minutes walking at a self-controlled pace between overs served to mimic the demands of fielding between overs in a game (Payne et al., 1987). All bowlers were given a standard warm-up of gentle jogging for ten minutes, followed by a pre-set stretching routine. The mean of three stature measurements were recorded on arrival and after the 2nd, 4th, 6th and 8th overs in Study 1. Curvature measurements were taken prior to warm-up and after the required overs had been bowled in each study.

In Studies 2 and 3 testing occurred on two separate sessions, one week apart and at the same time of day to minimise any circadian variations. Study 2 used a randomised cross over design to investigate between day intra-rater reliability, and both within day and between day inter-rater reliability of the Spinal Mouse measurements in the sagittal and frontal planes. Rater 1 and Rater 2 completed the measurement of participants in a randomised order (see Figure 2.5). For inter-rater reliability measurements marks on the spinous processes were wiped away before the second rater carried out their set of sagittal and frontal measurements. Each rater carried out the measurements three times with the mean recorded.

Study 3 measured within-day and between-day intra reliability of the custom-built stadiometer. Measurements were taken on arrival, post 20 minutes unloading in the Fowler position, after the warm-up, and post the 2^{nd}, 4^{th} and 6^{th} overs (see Figure 2.6). prior to testing all participants visited the laboratory for a familiarisation study which required them to remain within the stadiometer for 10 measurements as proposed by Stohart & McGill (2000). Acceptable within-day intra-reliability for participants was assumed when ten successive measurements showed a standard deviation of ≤ 0.5mm (Garbutt et al 1994; Reilly and Chana 1994; Dowzer et al 1998).

Pre-bowling	Post-bowling	Pre-bowling	Post-bowling
Rater 1 Mark spine Sagittal Measure Frontal measure Rater 2 Mark spine Sagittal Measure Frontal measure	Rater 1 Mark spine Sagittal Measure Frontal measure Rater 2 Mark spine, Sagittal Measure Frontal measure	Rater 1 Mark spine Sagittal Measure Frontal measure Rater 2 Mark spine Sagittal Measure Frontal measure	Rater 1 Mark spine Sagittal Measure Frontal measure Rater 2 Mark spine Sagittal Measure Frontal measure

Order of rater measurements and plane measurements randomised for day 1 and day 2.		
Intra-reliability	*Within-day inter-rater reliability*	*Between-day inter-rater reliability*
Rater 1 pre-bowling	Rater 1 v Rater 2 pre-bowling	Rater 1 v Rater 2 Pre-bowling
Rater 2 pre-bowling	Rater 1 v Rater 2 post-bowling	Rater 1 v Rater 2 Post-bowling
Rater 1 post-bowling		
Rater 2 post-bowling		

Figure 2.5 – Protocol for sagittal and frontal plane reliability measurements of spinal curvature using the Spinal Mouse (Study 2)

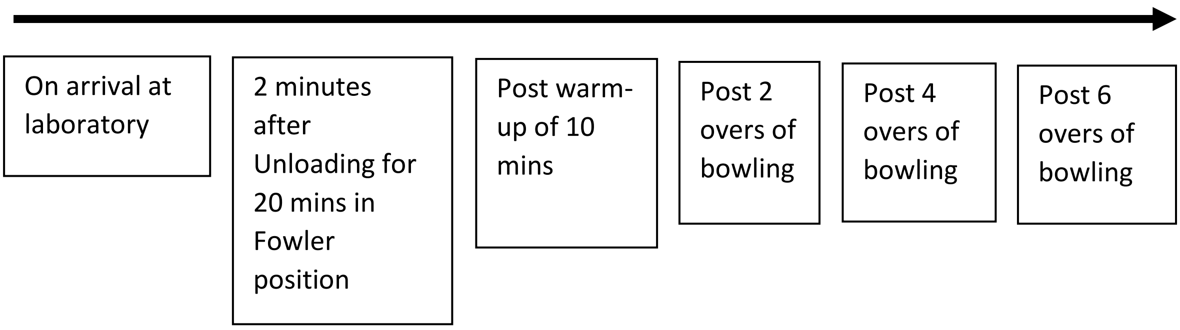


Figure 2.6 - Timing protocol for measuring spinal shrinkage using a custom-built stadiometer based on Eklund and Corlett (1984) (Study 3)

2.2.6 Statistical analysis

The normality of the data was examined and confirmed using the Shapiro-Wilk test, and test-retest score differences and mean scores were correlated to examine for heteroscedasticity (Atkinson & Neville 1998). In Studies 1 and 3 a One-Way Repeated Measures Analysis of Variance (ANOVA) was conducted to compare the effect of overs bowled on spinal shrinkage using the custom-built stadiometer. Mauchly's test of sphericity was conducted; and when not satisfied, a Greenhouse-Geisser correction was applied. Curvature was analysed under the classification values proposed by López-Miñarro et al., (2017). Thoracic kyphosis was neutral for values between 20° and 45°, with hypokyphosis below 20° and hyperkyphosis above 45°. Lumbar lordosis values between 20° and 40° were considered neutral, with hypolordosis below 20° and hyperlordosis above 40°. Paired sample t-tests were used to analyse the effect of bowling on curvature in Study 1. A Pearson Product Moment Correlation was used to determine the relationship between spinal shrinkage after eight overs and thoracic and lumbar curvature pre and post bowling in Study 1, with a significance set at $p<0.05$.

In Studies 2 and 3 reliability was calculated using Intra-class Correlation Coefficient (ICC3,1 - where the "3" refers to the type of ICC in which the subjects is a random effect and the trials is a fixed effect, while the "1" refers to the reliability of single repeated measurements). ICC was calculated as $1\text{-}TE^2$ divided by mean between participant standard deviation between trials) and Typical Error (TE) (calculated as standard deviation of the change scores between trials divided by square root of 2). ICC and the TE are reported with 95% confidence intervals in parenthesis. Both the ICC provides an indication of agreement between trials including rank order, whereas TE provides an indication of the error expected from measurement to measurement (Hopkins 2000). Currier's (1990) criteria for reliability were adopted for ICCs, with 0.90-0.99 = high reliability, 0.8-0.89 = good reliability, 0.70-0.79 = fair reliability and <0.69 = poor reliability.

In Study 2 within-day and between-day intra-rater and inter-rater reliability were calculated for lumbar lordosis using the Spinal Mouse, again using the ICC and TE. A 2x2 factorial ANOVA also served to examine the effect of the two raters, pre- and post-bowling on two separate days, on the means of lumbar lordotic angles in the sagittal and frontal planes using the Spinal Mouse. Significance level was set at $p \leq 0.05$ and all statistical tests were conducted with SPSS version 24.

2.3 Results

2.3.1 Study 1 - Alterations in stature and curvature after eight overs of fast bowling.

All bowlers had good within-day intra-rater reliability demonstrating ten successive stature measurements with a standard deviation of ≤0.5mm, thus all were deemed to be successfully trained on the use of custom-built stadiometer.

A significant main effect was found for overs on stature ($F_{1,10} = 37.33$, $p<0.001$) (see Figure 2.7). Bonferroni post hoc tests showed a significant loss of height (shrinkage) between pre-measurements and the 2nd, 4th, 6th & 8th overs ($p< 0.001$). Statistically significant shrinkage was also demonstrated between the 2nd and 4th and 2nd and 8th overs ($p<0.05$).

No significant differences were found in lumbar lordosis or thoracic kyphosis in upright standing, flexed and hyperextended positions after eight overs of bowling ($p>0.05$). Neither were significant differences found for any of the frontal plane curvature measurements after eight overs ($p>0.05$) (see Table 2.1). Hypolordosis in the lumbar spine was found in 25% of bowlers with 75% classified as neutral, and no changes seen after bowling. 75% of bowlers were classified with thoracic hyperkyphosis before bowling, which reduced to 50% after 8 overs. Conversely neutral classification rose from 25% to 50% after 8 overs.

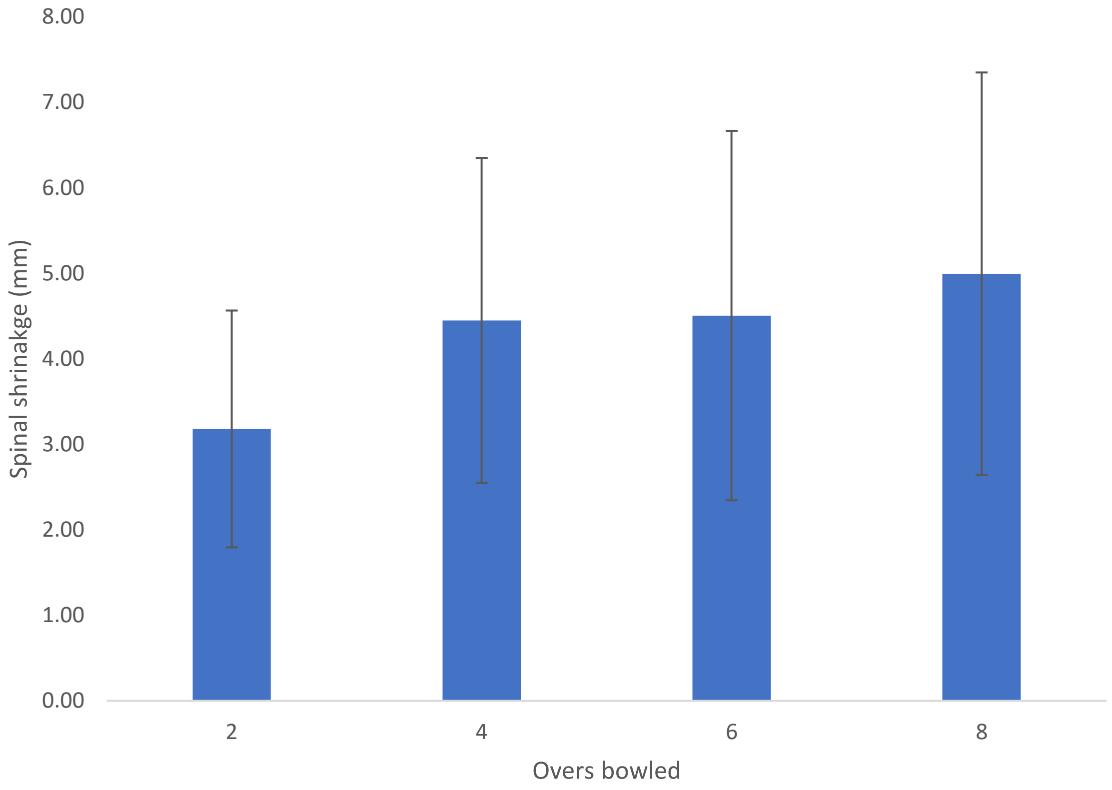


Figure 2.7 Mean (±SD) spinal shrinkage during eight overs of fast bowling

Table 2.1- Mean (±SD) spinal curvature (degrees) before and after 8 overs of fast

	Pre-Bowling Degrees	Over 8 Degrees
Sagittal Plane		
Thoracic Upright (STU)	45.1 (±9.6)	46.2 (±8.9)
Lumbar Upright (SLU)	-27.9 (±7.2)	-28.1 (±8.3)
Thoracic Flexion (STF)	57.7 (±9.7)	58.5 (±11.0)
Lumbar Flexion (SLF)	30.1 (±20.8)	35.8 (±20.8)
Thoracic Extension (STE)	30.2 (±20.6)	35.8 (±20.8)
Lumbar Extension (SLE)	-42.2 (±6.8)	-42.4 (±7.4)
Frontal Plane		
Thoracic flexion to left	30.7 (±4.4)	33.5 (±6.8)
Thoracic flexion to right	33.1 (±11.3)	32.6 (±6.9)
Lumbar flexion to left	23.8 (±6.8)	24.5 (±7.1)
Lumbar flexion to right	26.7 (±3.6)	27.7 (±5.1)

After 8 overs, no significant correlations were found between spinal shrinkage and sagittal lumbar and thoracic curvature in the upright, flexed, and extended positions ($p>0.05$).

2.3.2 Study 2 - Within and between day reliability of Spinal Mouse measurements of lumbar curvature in the sagittal and frontal planes.

Sagittal spinal curvature before bowling showed good between-day intra-rater reliability for the lumbar upright (SLU) position with an ICC for rater 1 and rater 2 of 0.81 (0.51-0.93) and 0.88 (0.67-0.96). After six overs a higher between-day intra-rater reliability ICC of 0.94 (0.84-0.98) for rater 1 and 0.93 (0.79-0.97) for rater 2 was shown (see Tables 4 & 5). Prior to bowling, TE for SLU was 3.50° (2.59°-5.57°) for raters 1 and 2, with the 6th over yielding values of 1.96° (1.45-3.12°) and 2.46° (1.82-3.92°) respectively (see Tables 2.4 & 2.5).

Significant main effects were found between raters for SLU curvature ($F_{1,10}$ = 11.2, p=0.007), with rater 2 recording a value of 4.75° (p= 0.007) lower than rater 1 (p=0.007;see Tables 2.2 & 2.3). No significant main effects were found for bowling or days on SLU curvature, and for raters, bowling or days for sagittal lumbar flexion (SLF) and sagittal lumbar extension (SLE) measurements (p>0.05). There were no significant interactions for raters, bowling or days on SLU, SLF and SLE (p>0.05).

Table 2.2 – Mean (±SD) spinal curvature (degrees) pre- and post- eight overs of bowling in the sagittal and frontal planes between day 1 and 2 for rater 1.

	Rater 1 pre bowling		Rater 1 post bowling	
Position	Day 1	Day 2	Day 1	Day 2
Sagittal				
Lumbar upright	-33.2 (±6.6)	35.1 (±7.8)	-33.4 (±7.2)	-36.3 (±7.4)
Lumbar flexion	33.4 (±4.4)	30.3 (±2.6)	32.2 (±5.0)	31.4 (±4.1)
Lumbar extension	-49.5 (±7.4)	-49.5 (±9.5)	-46.4 (±13.0)	-49.5 (±9.9)
Frontal				
Lumbar upright	25.2 (± 4.9)	24.0 (±5.0)	23.5 (±9.5)	22.4 (±3.8)
Lumbar left	6.6 (±3.4)	6.5 (±2.8)	7.3 (±2.8)	5.0 (±2.2)
Lumbar right	20 (±4.9)	20.7 (±5.3)	19.4 (±5.4)	20.5 (±6.0)

Table 2.3 – Mean (±SD) spinal curvature (degrees) pre- and post-eight overs of bowling in the sagittal and frontal planes between day 1 and 2 for rater 2.

	Rater 2 pre bowling		Rater 2 post bolwing	
Position	Day 1	Day 2	Day 1	Day 2
Sagittal				
Lumbar upright	-29.6 (±6.6)	-30.7 (±8.6)	-31.0 (±7.5)	-31.2 (±8.5)
Lumbar flexion	32.8 (±4.4)	31.4 (±2.9)	32.5 (±3.6)	31.3 (±2.7)
Lumbar extension	-44 (±11.1)	-46.8 (±12)	-46.6 (±11.1)	-45.6 (±7.9)
Frontal				
Lumbar upright	23.5 (±7.6)	25.5 (±5.7)	22.5 (±7.7)	24.5 (±4.3)
Lumbar left	6.9 (±3.7)	7.1 (±2.0)	7.3 (±3.4)	6.3 (±2.8)
Lumbar right	22.3 (±4.3)	22.1 (±4.9)	20.7 (±5.7)	21.9 (±6.4)

Table 2.4 - Intra-rater reliability of spinal curvature in sagittal and frontal planes pre-and post-eight overs of bowling between day 1 and 2 for rater 1.

	Rater 1 pre day 1 v pre day 2		Rater 1 post day 1 v post day 2	
Position	ICC (95% CI)	Typical error (95% CI) °	ICC (95% CI)	Typical error (95% CI) °
Sagittal				
Lumbar upright	0.81(0.51-0.93)	3.50 (2.59-5.57)	0.94 (0.84-0.98)	1.96 (1.45-3.12)
Lumbar flexion	0.63 (0.20-0.86)	2.33 (1.72-3.72)	0.42 (-0.10-0.76)	3.59 (2.65-5.72)
Lumbar extension	0.69 (0.29-0.88)	5.11 (3.78-8.14)	0.60 (0.15-0.85)	7.72 (5.71-12.30)
Frontal				
Lumbar upright	0.38 (-0.14-0.74)	5.36 (3.96-8.54)	0.54 (0.06-0.82)	5.14 (3.80-8.18)
Lumbar left	0.56 (0.09-0.83)	2.20 (1.63-3.51)	0.43 (-0.09-0.76)	2.00 (1.48-3.19)
Lumbar right	0.50 (0.0-0.8)	3.78 (2.80-6.03)	0.79 (0.49-0.93)	2.83 (2.09-4.50)

ICC = Intraclass correlation coefficient   CI = Confidence interval

Table 2.5 - Intra-rater reliability of spinal curvature in sagittal and frontal planes pre- and post-eight overs of bowling between day 1 and 2 for rater 2.

	Rater 2 pre day 1 v pre day 2		Rater 2 post day 1 v post day 2	
Position	ICC (95% CI)	Typical error (95% CI) °	ICC (95% CI)	Typical error (95% CI) °
Sagittal				
Lumbar upright	0.88 (0.67-0.96)	3.50 (2.59-5.57)	0.93 (0.79-0.97)	2.46 (1.82-3.92)
Lumbar flexion	0.77 (0.45-0.92)	1.93 (1.43-3.08)	0.45 (-0.07-0.77)	2.47 (1.83-3.94)
Lumbar extension	0.83 (0.58-0.94)	5.27 (3.90-8.40)	0.73 (0.36-0.90)	5.45 (4.03-8.68)
Frontal				
Lumbar upright	0.51 (0.02-0.81)	4.90 (3.62-7.80)	0.79 (0.49-0.93)	3.09 (2.28-4.92)
Lumbar left	0.25 (-0.28-0.66)	2.64 (1.95-4.21)	-0.13 (-0.59-0.4)	3.29 (2.43-5.24)
Lumbar right	-0.23 (-0.65-0.31)	5.08 (3.75-8.09)	0.62 (0.17-0.85)	3.99 (2.95-6.35)

ICC = Intraclass correlation coefficient   CI = Confidence interval

In the case of frontal lumbar flexion to the left (FLL) and frontal lumbar flexion to the right (FLR), there were no statistically significant main effects for rater, bowling or days ($p>0.05$). Lumbar flexion upright (FLU) had no main effects for rater or days ($p>0.05$). There were also no statistically significant interactions for rater, bowling and days for FLU and FLR ($p>0.05$).

Pre-bowling within day inter-reliability was high for lumbar flexion (ICCs 0.90 (0.74-0.97)) and good for the lumbar upright position in the sagittal plane (ICC ranges 0.89 (0.70-0.96) - 0.80 (0.50-0.93). Lumbar measurements showed poor to fair within-day inter-rater reliability (ICC 0.53 (0.04-0.81) - 0.78 (0.46-0.92) for post bowling in the sagittal plane. Within-day TE ranged from 1.38° (1.02°-2.20°) to 8.11° (6.00°-12.93°) (see Table 2.6). SLU showed fair between-day inter-reliability both pre and post bowling (ICC 0.78 (0.46-0.92)) and good inter-rater reliability for SLF pre bowling (ICC 0.80 (0.5-0.93) (see Table 2.7).

From the frontal parameters measured pre and post bowling, good within-day pre bowling inter-rater reliability was demonstrated for lumbar upright (ICC 0.83 (0.56-0.94) and lumbar right lateral bend (ICC 0.88 (0.67-0.96)). Poor within and between-day inter-reliability was demonstrated in all other frontal parameters (see Tables 2.6 & 2.7). Frontal TE ranged from 2.45° (1.81°- 3.91°) - 6.26° (4.63°-9.98°) for all inter-rater measurements.

Table 2.6 Within-day inter-rater reliability of spinal curvature in sagittal and frontal planes pre- and post-bowling.

	Rater 1 pre-day 1 v Rater 2 pre-day 1		Rater 1 post-day 1 v Rater 2 post-day 1	
Position	ICC (95% CI)	Typical error (95% CI °)	ICC (95% CI)	Typical error (95% CI) °
Sagittal				
Lumbar upright	0.81 (0.53-0.93)	3.81 (2.82-6.07)	0.75 (0.41-0.61)	3.96 (2.93-6.31)
Lumbar flexion	0.90 (0.74-0.97)	1.53 (1.13-2.44)	0.78 (0.46-0.92)	2.22 (1.64-3.54)
Lumbar extension	0.29 (0.24-0.69)	8.11 (6.00-12.93)	0.53 (0.04-0.81)	1.38 (1.02-2.20)
Frontal				
Lumbar upright	0.85 (0.60-0.95)	3.36 (2.49-5.36)	0.88 (0.67-0.96)	3.38 (2.50-5.39)
Lumbar left	0.58 (0.12-0.84)	2.45 (1.81- 3.91)	0.21 (-0.33-0.64)	2.85 (2.10-4.53)
Lumbar right	0.23 (-0.30-0.65)	4.11 (3.04-6.55)	0.83 (0.56-0.94)	2.55 (1.89-4.07)

ICC = Intraclass correlation coefficient   Cl = Confidence interval

Table 2.7 - Between day inter-rater reliability of spinal curvature in sagittal and frontal planes pre- and post-bowling.

	Rater 1 pre-day 1 v Rater 2 pre-day 2		Rater 1 post-day 1 v Rater 2 post-day 2	
Position	ICC (95% CI)	Typical error (95% CI) °	ICC (95% CI)	Typical error (95% CI) °
Sagittal				
Lumbar upright	0.78 (0.46-0.92)	3.96 (2.92-6.30)	0.78 (0.46-0.92)	4.05 (2.99-6.45)
Lumbar flexion	0.80 (0.5-0.93)	1.84 (1.36-2.94)	0.41 (0.11-0.75)	3.17 (2.34-5.05)
Lumbar extension	0.47 (0.03-0.79)	7.51 (5.55-11.96)	0.45 (0.06-0.77)	8.28 (6.12-13.20)
Frontal				
Lumbar upright	0.19 (-0.34-0.63)	6.26 (4.63-9.98)	0.66 (0.24-0.87)	4.59 (3.39-7.32)
Lumbar left	0.29 (-0.25-0.69)	2.44 (1.80-3.88)	-0.05 (-0.54-.45)	2.86 (2.12-4.56)
Lumbar right	0.31 (-0.22-0.70)	4.18 (3.09-6.65)	0.57 (0.10-0.83)	4.10 (3.03-6.54)

ICC = Intraclass correlation coefficient   CI = Confidence interval

2.3.3 Study 3 – Within-day and between-day reliability of spinal shrinkage.

All bowlers demonstrated within-day reliability with ten successive measurements on the custom-built stadiometer less than a standard deviation of 0.5mm. Between-day intra-rater reliability was poor for stature change when unloaded, and during a fast bowling spell of six overs, with ICCs ranging from 0.00 (0.00-0.29) to 0.49 (0.00-0.8). TE ranged between 2.53 mm (1.85-4.17 mm) – 5.42 mm (3.95-8.92 mm) (see Table 2.8).

Table 2.8 - Reliability of **s**pinal shrinkage pre, during and post six overs of bowling.

	Unloaded	Post warm-up	2nd over	4th over	6th over
ICC (95% CI)	0.16 (adj 0.00-0.63)	0.49 (adj 0.00-0.8)	0.34 (adj 0.00-0.73)	adj - 0.00 (adj 0.00-0..29)	adj 0.00 (adj 0.00-0.46)
Typical error (°) (95% CI)	3.44 (2.51-3.66)	2.53 (1.85-4.17)	4.28 (3.12-7.05)	4.60 (3.35-7.56)	5.42 (3.95-8.92)

ICC = Intraclass correlation coefficient; CI = Confidence interval; Adj = adjusted negative ICC to 0.00.

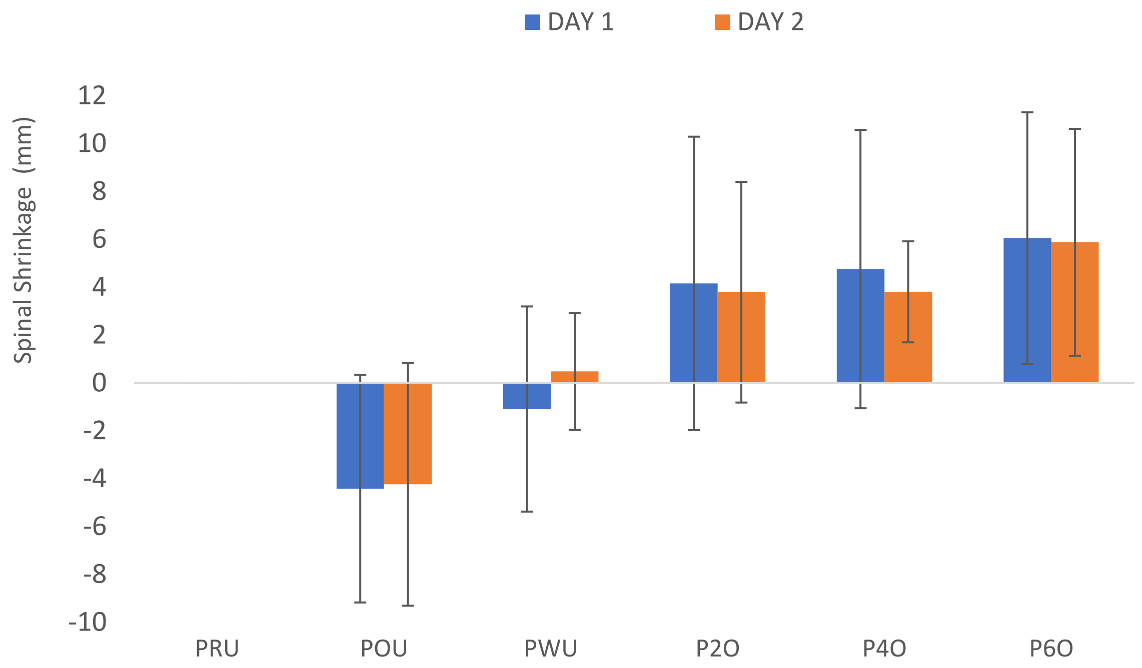


Figure 2.8 - Spinal shrinkage – pre unloaded (PRU), post unloaded (POU), post warm-up (PWU), and after the 2nd over (P2O), 4th over (P4O), 6th Over (P6O).

No significant differences were found in shrinkage between day one and day two for unloaded, post warm-up, 2nd, 4th and 6th overs ($p>0.05$). Spinal shrinkage differed significantly as a result of bowling on both day one ($F_{1.78, 16} = 25.97$, $p < .001$) and day 2 ($F_{1.83, 16.43} = 19.14$, $p < 0.001$). Bonferroni post hoc tests showed that the warm-up did not significantly increase shrinkage on either day ($p> 0.05$). On day 1, bowlers' stature significantly reduced by 8.57 mm (95% CI 2.07-15.08 mm) between the unloaded condition and after the second over ($p=0.009$). Significant shrinkage of 9.17 mm (95% CI 4.16-14.18 mm) and 10.47 mm (95% CI 5.78-15.16 mm) occurred between unloaded and the 4th ($p=0.001$) and 6th overs ($p<0.001$) respectively. Significant shrinkage was also found between post warm-up and the 2nd ($p= 0.026$), 4th ($p=0.019$), and 6th overs (7.14 mm, 95% CI 2.32 – 11.96, $p=0.004$). On day 2 significant shrinkage occurred between the unloaded condition and the 4th over (p=0.037) and the 6th over (10.11 mm, 95% CI 0.21 – 20.01 mm, p=0.044). The same was true between post warm-up and the 4th over (p=0.029) and 6th over (5.4 mm 95% CI 0.37 – 10.43 mm, p=0.033). No significant differences in shrinkage were observed between the 2nd, 4th and 6th overs (p>0.05) on both days of testing (see Figure 2.8).

2.4 Discussion

Fast bowling between six and eight overs placed a noteworthy spinal load on the bowlers accounting for 25-35% of a predicted maximal diurnal shrinkage of approximately 20 mm (Eklund & Corlett 1987). A plateau in shrinkage occurred after the second and fourth overs in Studies 3 and 1 respectively. Spinal curvature was not altered by the acute effects of fast bowling in the club standard fast bowlers when measured with the Spinal Mouse. This finding further supports the assumption that a loss in stature is due to alterations of the intervertebral discs in response to the load of fast bowling. The Spinal Mouse demonstrated good to high between-day reliability for both raters when measuring sagittal lumbar lordosis in the upright position. Within-day inter-rater reliability was also proved to be good for the same measurement pre-bowling. The custom-built stadiometer based on the design of Eklund & Corlett (1984) demonstrated good within-day intra-reliability for 10 successive measurements prior to bowling. However, it did not provide adequate reliability for between-day intra-rater reliable measurements of stature changes during the five conditions (i.e., unloaded, post warm-up, 2nd, 4th and 6th over).

Rodacki et al. (2001) recommended sufficient familiarization sessions when using a custom-built stadiometer, so that participants achieve an accepted level of reliability. All bowlers in Studies 1 and 3 achieved 10 measurements with an SD of <0.5mm, the most used criterion for confirming the participant can repeat stature measurements (Garbutt et al. 1990, Fowler et al. 1997; Rodacki et al. 2001). The poor between-day intra-rater reliability when using the stadiometer on the other hand, needs exploring.

Previous research using similar apparatus, conducted on participants with and without chronic low-back pain, also demonstrated poor reliability for measurements in the unloaded condition and in the first 10 minutes of loading (Kanlayanaphotporn et al., 2002). In contrast, Healey et al. (2005) reported an ICC (1,1) of 0.99 for control and chronic low-back pain groups (12 in each group). The Typical Error in study 3 ranged from 2.53 mm (1.85-4.17mm) to 5.42 mm (3.95-8.92mm) which is much higher than in previous research. Healey et al. (2005) demonstrated TE values of 0.043 mm and 0.041 mm in CLBP and control groups, respectively, while Kanlayanaphotporn et al. (2002) reported a range of TE 1.02-1.98 mm.

Healey et al. (2005) suggested that three sets of measurements are optimal to achieve the desired SD (<0.5 mm). Studies 1 and 3 showed that participants can repeat the measurements to a SD of <0.5mm in one familiarisation session, if they follow the protocol of remaining in the stadiometer for the 10 measurements as advocated by Stohart & McGill (1999). The subsequent conditions (unloading, loading through warm-up, and bowling), necessitated the participants move in and out of the stadiometer between measurements, which may have contributed to the poor between-day reliability and large TE in Study 3. As the results of that Study 3 indicate, participants having been trained to ensure repeatable measurements does not guarantee between-day reliability. If measurements are to be made on a population of active individuals such as fast bowlers, then there may be a need to train the participants on each visit to the laboratory.

The focus in the literature has been on participants being able to repeat the measurements but there has been no mention of the training needed by the experimenter or rater. Inconsistencies in the measurement protocol undertaken by the raters could be linked to participants who have just finished a physically demanding task and may have difficulty remaining still in the stadiometer. The ability of the bowler to maintain postural integrity and replicate the correct measurement position may have hindered the correct placement of the postural rods. Maintaining head position is crucial to the success of the measurements and was achieved with the help of two infra- red lasers on either side of a spectacle frame pointing upwards (Healey et al., 2008, Lewis & Fowler 2009). Having the one size frames meant that no account was taken of different head sizes and concomitant movement. Having to align two lasers may have increased the error, so other authors have used a single light emitting laser located on bridge of spectacles pointing in a forward direction (Leatt et al., 1986, Reilly & Freeman 2006).

Participants achieving a relaxed state immediately after strenuous exercise such as fast bowling represents a significant challenge to the researcher. The paucity in previous literature of reliability studies over separate days and the variety of adaptations of the original Eklund & Corlett (1984) stadiometer model suggest that each variant on the original design should undergo within-day and between-day reliability testing to ensure that both the rater and the participant are trained to use the equipment. Future investigations of active populations, such as fast bowlers, should consider the amount of practice and time required to attain the appropriate level of within-day and between-day reliability. Rather than following the approach of Stohart & McGill (1999), where participants remain in the stadiometer for 10 repeatability measurements, research should ensure that the method of moving in and out of the stadiometer in the same way that field measurements are taken, is also part of the procedure.

The time taken for training reliability in a custom-built stadiometer has been shown to be influenced by coordination and proprioceptive qualities (Van Dieen and Toussaint 1993), which could have contributed to the error measurements. Participants were trained within one familiarisation session with no one session taking longer than 45 minutes. This compares favourably with the mean training time of 46 minutes for Reilly and Chana's (1994) study on fast bowling, although Corlett et al. (1987) stated that for some participants training took more than one hour. It is possible that although participants achieved the repeatability standard of 10 measurements with an SD of <0.5 mm they were still not fully trained to undertake the shrinkage measurement after exercise. The time needed for reliability training raises questions regarding the ecological validity of using such a stadiometer in a field setting. If future research goals include establishing the clinical significance of shrinkage within a sporting population in the field, such modified equipment may not be suitable and other solutions may need to be found. The ethical dimension of exposing participants to such an arduous testing regime with potentially poor reliability must also be considered. For example, testing lasting up to an hour, adds to a bowler's workload and potentially detracts from valuable technical and physical training, especially in the case of elite performers.

The poor reliability is indicated by negative ICC levels reported in Table 8. Since ICCs are defined to be the proportion of between-subjects variance, theoretically they should range from 0 to 1. In practice, the negative ICC can be due to the variance in sample size. If the TE is larger than the between group SD, as found for the shrinkage measurements of the custom-built stadiometer, then the ICC will be negative. In the current study large variance within the small sample size of 11 is the cause of the negative value. Due to this sampling uncertainty, the calculated values of ICCs were out of the theoretical range, so to make the negative ICC values meaningful they were adjusted to zero as suggested by Salthouse (1994) (see Table 2.8).

Despite poor reliability, overall shrinkage during bowling ranged from of 4.99 ± 2.35 mm to 6.05 ± 5.26 mm in Studies 1 and 3 (without unloading), respectively. These values are higher than previous research and Study 3 measures demonstrate larger standard deviations that shows greater variability (Reilly and Chana 1994; Barry 2007). This is likely due to the different protocol used with Study 3 with the additional measurement of 15 minutes unloading in the Fowler position prior to warm-up and subsequent bowling. The different individual effects of unloading on stature gain have potentially led to an increase in the variance of subsequent shrinkage measurements duirng the warm-up and bowling. Whereas previous research reported a linear increase in stature loss as bowling progressed (Reilly and Chana 1994; Barry 2007), this is the first study to demonstrate a plateau in shrinkage between the second and fourth overs. This is of potentially greater significance since a plateau in shrinkage may imply that the shock absorbing capacity of the intervertebral discs is reduced as bowling continues beyond four overs. Further research is required to determine the exact pattern of stature loss during fast bowling.

Because hyperlordosis has been associated with lumbar stress injuries (Been & Kalichman 2014), it is important to have a reliable device for measuring lumbar curvature that does not expose the patient to unnecessary ionising radiation. Study 2 demonstrated that the Spinal Mouse has high to good between-day intra-reliability for 2 raters measuring sagittal lumbar lordosis in the upright position. This is in agreement with previous research using the same device, which has shown high within-day intra-rater reliability for the same measurement with ICCs ranging from 0.90 – 0.98 and Typical Errors of 1.7° – 2.5° (Keller et al., 2000; Manion et al., 2004; Roghani et al., 2004 Topalidou et al., 2015). Similarly, within-day inter-rater reliability was good pre-bowling for the sagittal lumbar upright position with fair between-day inter-rater reliability both pre- and post-bowling. These results confirm that the Spinal Mouse is a reliable device, for sagittal curve measurements of the lumbar spine in the upright position in fast bowlers. Moreover, when implementing Spinal Mouse measurements during studies lasting multiple days or weeks, best results will be obtained by using the same rater.

The reliability of the Spinal Mouse when measuring in the flexed and extended positions was somewhat mixed. Between-day intra-rater reliability was poor for lumbar measurements in both positions, whilst within-day inter-rater reliability was high for lumbar flexion and poor for extension. These results agree with Kellis et al. (2008) who reported a greater range of ICC measures (0.61-0.92) for lordosis in flexion and extension but contrast with Manion et al., (2004) reported good reliability for these measurements. The uncertainty of measurements in the flexed and extended positions is likely due to the variability of individuals in reaching these positions. The protocol requires the mean measure to be taken from the three trials and repeating the same flexed and extended position proved difficult for some bowlers. Similarly, for post bowling poor to fair within-day inter-rater reliability was found for flexed and extended positions, highlighting the differential effect that eight overs of bowling had on the range of movement for each bowler. These results are consistent with previous between-day inter-rater reliability that ranged from poor to high (ICC 0.61 – 0.96) for sagittal upright, flexion and extension lumbar measurements, albeit with a much younger population (Kellis et al., 2008). The same authors also reported Typical Error between 1.47° – 7.58° for the same measurements, which are similar to those reported in Study 2.

For raters to reach a good level of reliability, below a TE of 3.5° they must be aware of issues that may affect the measurement process (Kellis et al 2008; Roghani et al 2017). For example, when using the Spinal Mouse, they must consider adipose tissue overlying the spinous processes and the morphology of lumbar muscles (Manion et al 2004). The ability to palpate the correct bony landmarks and follow the midline with the device and apply the correct pressure may all influence results (Kellis et al., 2008; Ripani etal., 2008). Maintaining the correct, repeated posture and utilising a standardized protocol with experienced testers have been reported as essential to reduce error (Kellis et al 2008; Roghani et al 2017). Clearly, more research is needed to determine the reliability of using the Spinal Mouse to measure lumbar lordosis in flexion and extension positions in an adult athletic population.

Poor within- and between-day inter-rater reliability in nine out of the 12 frontal plane parameters demonstrates the need for caution in the use of skin surface devices in this plane. The protocol for measuring the spine in the frontal plane requires the rater to mark the spinous processes along the spine and follow the contours of the marks when measuring in all positions. The assumption is that the marks reflect the vertebral bodies (Manion et al., 2004) but as the participant flexes laterally to the left and right, the marks made on the spine move away from the spinous processes. This affects the accuracy and reliability of the measurements. It is therefore recommended that the Spinal Mouse not be used for frontal plane measurements with fast bowlers.

To the author's knowledge this is only the second study to report curvature of fast bowlers. Hecimovich & Stomski (2016) measured lordosis in male and female bowlers using a flexicurve which resulted in a different calculation for the lordotic angle, thus making a direct comparison of absolute values difficult. In Study 1 upright sagittal thoracic kyphosis (45.1 ±9.6°) and lumbar lordosis (-27.9 ±7.2°) in fast bowlers equated to Spinal Mouse measurements from other athletic populations. Tennis players reported kyphotic and lordoctic angles of 43.83 ±7.87° and -27.58 ±7.01° respectively (Muyor et al., 2013a), whilst Lopez-Miñarro and colleagues found similar results for canoeists (kyphosis 44.66 ±8.80°; lordosis -30.34 ±8.31°) and kayakers (kyphosis 44.5 ±7.61°; lordosis -27.27 ±7.06°). Muyor et al. (2011) also reported a mean lordotic angle of -27.32 ±7.23° for cyclists.

Hyperlordosis in the lumbar spine was observed in sagittal upright position in 23% of bowlers and in neutral position in 77% and remained the same after bowling. Thoracic classifications were split equally between hyperkyphosis (50%) and neutral (50%) for all bowlers. These results accord with reported thoracic and lumbar spines of canoeists (Lopez-Minaro et al., 2011).

Lumbar lordosis and thoracic kyphosis have geometric properties that influence mechanical properties of the spine during compressive loading. The noteworthy occurrence of hyperlordosis and hyperkyphosis in the current population of club standard fast bowlers may be due to exposure to intensive training (Wojtys et al., 2000). Arlicsson & Werner (2006) found increased thoracic kyphosis in skiers after a period of 5 years intensive training, whist Förster et al. (2009) reported high lordotic and kyphotic angles in climbers. Increasing curvature angles in both lumbar and thoracic regions of the spine has been associated with larger shear forces (McGill 2015), greater intradiscal pressures (Wilke et al., 2001) and an increased risk of stress fractures particularly in the lumbar spine (Been &

Kalichman 2014). The link reported by Hecimovich & Stomski (2015) between hyperlordosis and back pain in junior level fast bowlers highlights the need for further investigation into whether such morphology might be a risk factor associated with injury to the spine in elite fast bowlers.

Study 1 found no acute effect of bowling six overs on spinal curvature. Limited research evidence is available on the acute effects of physical activity or sporting action on the curvature of the spine. Similarly, Lopez Miñarro et al. (2012) investigated the acute effect of eight minutes of hamstring stretching on upright curvatures and found no difference between prior and post measurements. Although loading the spine during bowling appears to influence spinal shrinkage, curvature in the upright position remains unaltered. Furthermore, no correlation exists between shrinkage and curvature measurements either before or after bowling. Therefore, it is likely that loss of stature during is related to disc height loss rather than any change in lordosis and future research with fast bowlers should measure both spinal shrinkage and curvature.

2.5 Conclusion

Results from the Spinal Mouse reveal that lumbar and thoracic curvature is not altered by the acute effects of fast bowling in club standard fast bowlers. Within this population, the Spinal Mouse is a reliable device for measuring sagittal curves of the lumbar and thoracic spine in the upright position. For enhanced between-day reliability the same trained rater is recommended for repeated measurements with this device.

Six to eight overs of fast bowling have been shown to place a considerable load on the spine as indicted by stature loss. When measuring shrinkage, the custom-built stadiometer shows good within day-intra-rater reliability, but it is not reliable for use in populations that undertake vigorous exercise, such as fast bowling. As measurement of spinal shrinkage may play a role in identifying injury risk in fast bowlers, alternative devices that use modern technology and lend themselves easily to application in the field need to be sought.

Chapter 3 – Reliability and validity of the Seca 287 ultrasound stadiometer for measuring stature and spinal shrinkage.

3.1 Introduction

Stature is normally obtained with a stadiometer that has a moveable head caliper. Such commercially available stadiometers are widely recognised for within and between rater reliability, when measuring the height of children (Ayle et al., 2012; Voss et al., 1990; Voss et al., 1994; De Miguel-Etayo et al., 2014), adults (Geeta et al., 2009; Bahrudin et al 2017) and the elderly (Gomez-Cabello et al., 2012). Moreover, reliability does not appear to be compromised by the type/cost of most devices used in medical settings (Voss et al., 1990; Voss et al., 1994). Intra-rater reliability is also either similar to (Geeta et al., 2009; Bahrudin et al 2017) or slightly better than (Ayle et al., 2012; Gomez-Cabello et al., 2012; De Miguel-Etayo et al., 2014) inter-rater reliability. Voss et al., (1990) reported that experienced raters generally produce more reliable measures than those who are inexperienced. Nevertheless, the same authors also noted a significant difference (0.20 cm) in the mean height of the same children measured by two experienced observers, due to differences in their measuring techniques. Whilst such differences may appear trivial in the detection of height changes during growth, they may be clinically important in the measurement of spinal shrinkage.

In contrast to previously reported research, which used controlled, experimental conditions, Mikula et al. (2016) assessed the reliability of 32 stadiometers by comparing multiple height measures obtained from patient records. Their results found that incorrect installation of devices and failure of staff to follow recommended guidelines resulted in 18% of patients' measurements differing by up to 2 cm over three months. By measuring a rod of known length, spot checks of stadiometers in medical centres also revealed that incorrect installation led to errors of between -1.3 cm to +1.1 cm (Geeta et al., 2009), and >1.5 cm (Mikula et al., 2016). Correct installation was shown by Voss et al., (1994) to improve accuracy across a range of height measuring devices to ±0.1 cm.

The Seca 287 (Seca, Gmbh, Hamburg, Germany) is a sophisticated stadiometer that uses three pairs of ultrasonic sensors to measure height with a resolution of 1 mm. Elia et al.

(2019) evaluated the use of this sonic technology to measure stature in healthy and malnourished populations. Intra-rater reliability showed a TE 1.86 mm for healthy participants and 3.68 mm for patients. The results were compared to measurements taken on a mechanical stadiometer using a head caliper, but validity of the device was not investigated.

As stated in the previous chapter, alterations in the height of participants in response to loading and unloading has also been used to estimate indirectly intervertebral disc (IVD) height changes and is termed 'spinal shrinkage' (e.g Tyrrell et al., 1985; Munster et al., 2018). Pennell et al. (2012) assessed whether a commercially available stadiometer (measurement resolution = 1 mm) would be able to detect such small changes in stature that have been observed, for example, during walking in a weighted vest (mean = 0.54 cm) (Healey et al., 2008), running (mean = 0.46 cm) (Dowzer et al., 2008), circuit training (mean = 0.49 cm) (Reilly & Freeman 2006) and fast bowling (mean = 0.23 cm) (Reilly & Chana 1984), which have traditionally been assessed using a high resolution custom made stadiometer. Users of custom-built stadiometers strive for high repeatability of ten measurements (SD <0.5 mm) during familiarisation where participants stay in the device (Healey et al., 2005). However, due to postural as well as measurement variability, repeatability is not as good when participants step in and out of the device between measurements (SD = 0.84 mm to 1.3 mm) (Stothart & McGill., 2000). Using the 'step-in-and-out' method in a commercially available stadiometer, Pennell et al.'s (2012) participants were able, after practice, to achieve a SD of <1.3 mm from five measurements in a seated position. Good intra and inter-rater reliability of the device over three subsequent loading sessions led the authors to conclude that commercially available stadiometers with high precision could extend the range of tools used for clinical research into the management of lower back pain (Pennell et al., 2012).

Aim – To investigate the reliability and validity of an ultrasound stadiometer for measuring stature and spinal shrinkage.

Objectives

- To determine the effect of instruction mode on the within-day and between day reliability of the Seca 287 ultrasound stadiometer (Study 4).

- To examine the between day intra-rater reliability of the Seca 287 Ultrasound stadiometer for measuring stature and spinal shrinkage (Study 5).
- To examine the concurrent validity of the Seca 287 Ultrasound stadiometer for measuring change in stature (Study 6).

3.2 Methods

The design consisted of three studies, two of which assessed reliability of measures taken with the Seca 287 (Studies 4 and 5), and a third (Study 6) which assessed the validity of the device. Study 4 assessed both within- and between-day reliability of height measurements before and after walking, using both automated and rater instructions. Study 5 investigated between-day intra-rater reliability, before and after five overs of cricket bowling, as well as the ability of the device to detect stature change in such a high loading environment. Concurrent validity was assessed in Study 6 by comparing Seca 287 measurements with those from a high-resolution custom-made stadiometer, before and after walking. All studies received ethical approval from Manchester Metropolitan University research Ethics Committee. In all three, participants were without shoes, and their measurements were taken after they had been standing for two minutes to allow any soft tissue changes to stabilise (Foreman & Linge 1989).

3.2.1 Study 4

Participants

16 male participants with a mean age of 20.3 (SD: ±1.9) years, a mean height of 178.9 (SD: ±6.0) cm and a mean body mass of 77.6 (SD: ±10.5) kg, who all reported no previous or current spinal injuries requiring hospitalisation or consultation with a physician, volunteered for the study.

Protocol

The Seca 287 was calibrated for height with an 81.5cm reference bar and was levelled using the in-built spirit level. Participants were asked to stand on the platform (16.5 cm width and 15 cm depth) and align their feet to two cardboard outlines of a size 9 foot placed on to the plate. This ensured repeatable foot placement for the participants so that measurements were taken vertically above the central point of the horizontal standing platform. Within-day reliability of the Seca 287 was assessed from ten measurements where each participant used the ‘step in and out’ method. For the first set of ten trials, participants followed the manufacturer’s recommended instructions through automated verbal guidance that stated: "*Please stand up-right and look straight, do not move, the measurement starts now*" (Seca Instruction).

For the second set of ten trials, participants were given more specific detailed instructions by the experimenter. This was to stand on the specific marks placed on the platform to align your heels and toes, keep both feet shoulder width apart, lock knees, relax shoulders, look straight forward and hold your breath after inhalation, while the automated verbal commands were muted (Experimenter Instruction). Participants then unloaded their spines in the Fowler position for 20 minutes (Tyrrell et al., 1985), after which a third set of ten (pre-walk) stature measurements was taken, again following the experimenter instructions (Pre-Walk). A fourth and final set of ten measurements were taken after participants had walked on a treadmill at a self-selected pace wearing a weighted vest (15% of body mass) for 10 minutes designed to load the spine (Healey et al., 2008) (Post-Walk). Between-day reliability was assessed by repeating the above protocol over a two-week period at the same time of day to account for circadian variation (Healey et al., 2008).

3.2.2 Study 5

Participants

Twelve male Cheshire Cricket Academy fast bowlers aged between 16-17 years, with a mean height of 180.3 (± 7.6) cm and a mean body mass of 64.6 (± 5.6) kg, who all reported no previous or current spinal injuries requiring hospitalisation or consultation with a physician, volunteered for the study.

Protocol

On the participants’ arrival at the indoor cricket facility a single, initial height (pre-unloading) measurement was obtained. Participants then adopted a supine position, with support under the knees for 20 minutes to unload the spine before a second (post-unloading) measure was taken. The bowlers completed a 10-minute warm up, similar to that which they would perform before a match, and consisting of 10 m high-speed running, high knees, heel flicks, sideways strides, lunges and dynamic stretches. After the warm-up, a third (pre-bowling) measurement was taken, before participants paired up to bowl in the nets at match-intensity. Each player bowled one over (i.e. six balls) whilst the other performed fielding exercises to mimic a match situation. At the end of each over the players switched roles until they had each completed five overs of bowling and fielding. They then had their final (post-bowling) measurement taken with the Seca 287, after which the next pair of bowlers was tested. This process was repeated at the same time one week later to assess the ability of the Seca to detect small changes in stature across days.

3.2.3 Study 6

Participants

Ten University students of mixed gender aged 21-25 years, with a mean mass of 77.6 (± 6.7) kg, and mean height of 168.3 (± 7.2) cm, who had been injury free for at least two months volunteered to take part in this study.

Protocol

Criterion validity of the Seca 287 was assessed by comparison of the measurements from that device with those from a custom-built stadiometer, similar to the one used by Healey et al. (2008). This device had a measurement resolution of 0.01 mm and was for the purpose of this study considered the ‘gold standard’ stadiometer (GSS).

After familiarisation with the GSS, their heights were measured using the Seca 287 followed by five stature measurements on the GSS, using the protocol from Studies 1 and 3 (see Section 2.2.2 Chapter 2), before a further measurement was taken using the Seca 287. The mean of the two Seca measurements and the five GSS measurements, were used as the pre-unloading values. Participants then adopted a supine position, with support under the knees for 20 minutes to unload the spine, as in Study 5, before the measurement process described above was repeated to provide the post-unloading values. Similar to Study 4, participants then walked at 3.5 $m \cdot s^{-1}$ on an inclined treadmill whilst wearing a weighted vest (10% body mass) for 15 minutes to induce minor fatigue and spinal shrinkage. Participants finally repeated the measurement process outlined above to furnish the post-walk values.

The GSS is designed to measure change in stature between different measurements rather than stature itself. Thus, the change in height between subsequent measures was calculated for both devices (i.e., post-unloading minus pre-unloading and post-walk minus pre-walk) to enable assessment of the concurrent validity of the Seca 287.

3.2.4 Statistical analysis

Within-day and between-day reliability were both assessed in Studies 4 and 5 using intraclass correlation (ICC) and typical error (TE), with 95% confidence intervals (CIs), as recommended and defined by Hopkins (2000). A paired *t*-test was also used to assess the effect of type of instruction on height measurements taken on each day in Study 4.

In Study 6, concurrent validity of the Seca 287 was assessed by a Pearson's Correlation Coefficient and with the help of Bland and Altman's Limits of Agreement (Bland & Altman 1986) between the change in stature measurements before and after unloading and walking. In all three studies, Repeated Measures ANOVAs were also used to assess the effect of different loading conditions on height measured by the Seca, Tukey's HSD post-hoc test was also applied where appropriate. All data met the assumptions of parametricity for each test, and significance was set to $p<0.05$.

3.3 Results

3.3.1 Study 4

Within-day reliability was excellent for the Seca 287 on both days, as demonstrated by both the high ICC and low TE values shown in Tables 3.1 and 3.2. On Day 1 use of the experimenter modified verbal instructions resulted in improved reliability over the automated Seca 287 instructions, as demonstrated by the lower TE (see Table 3.1). Conversely, use of the experimenter instructions made no difference to reliability of the height measurements on Day 2 (see Table 3.2). On both days, the type of instruction made no difference to the participants' height ($p > 0.05$). Reliability was also excellent between Day 1 and Day 2, although not as good as within-day reliability, as demonstrated by the higher TE in Table 3.3.

Height was significantly different between the loading conditions, on Day 1 (see Table 3.1, $F_{2,28} = 28.5$, $p < 0.001$) and Day 2 (see Table 3.2, $F_{2,28} = 29.0$, $p < 0.001$); on both days, participants, following the experimenter instructions, gained height during unloading (p<

0.01), and lost height between unloading and walking (p< 0.01). In comparison with the measurement on arrival, height was also significantly lower after walking, on Day 1 (p< 0.05), but not Day 2.

Table 3.1. Within-day stature, typical error (TE) and intraclass correlation (ICC) of Seca 287 measurements on Day 1 (10 trials, n = 16, walking).

	Stature (cm) Mean±SD	TE (cm) (95% CI)	ICC (95% CI)
Seca Instruction	178.2 ±7.0	0.42 (0.37-0.48)	1.00 (0.99-1.00)
Experimenter Instruction	178.4 ±7.1	0.23 (0.20-0.26)	1.00 (1.00-1.00)
Pre-Walk	178.8 ±7.1	0.30 (0.27-0.35)	1.00 (1.00-1.00)
Post-Walk	178.2 ±7.1	0.25 (0.22-0.29)	1.00 (1.00-1.00)

Table 3.2. Within-day stature, typical error (TE) and intraclass correlation (ICC) of Seca 287 measurements on Day 2 (10 trials, n = 16, walking).

	Stature (cm) Mean±SD	TE (cm) (95% CI)	ICC (95% CI)
Seca Instruction	178.8 ±7.1	0.25 (0.22-0.29)	1.00 (1.00-1.00)
Experimenter Instruction	179.3 ±6.9	0.26 (0.25-0.35)	1.00 (1.00-1.00)
Pre-Walk	179.3 ±7.1	0.26 (0.23-0.30)	1.00 (0.99-1.00)
Post-Walk	178.6 ±7.0	0.23 (0.20-0.27)	1.00 (1.00-1.00)

Table 3.3. Between day stature, typical error (TE) and intraclass correlation (ICC) of Seca 287 measurements (n = 16, walking).

	Stature (cm) Mean±SD	TE (cm) (95% CI)	ICC (95% CI)
Seca Instruction	178.7 ±7.0	0.39 (0.28-0.61)	1.00 (0.99-1.00)
Experimenter Instruction	178.8 ±7.0	0.30 (0.22-0.48)	1.00 (1.00-1.00)
Pre-Walk	179.3 ±7.1	0.36 (0.26-0.57)	1.00 (0.99-1.00)
Post-Walk	178.6 ±7.0	0.26 (0.19-0.42)	1.00 (1.00-1.00)

3.3.2 Study 5

The ICCs showed excellent between day reliability of the Seca 287 for the cricket bowlers and TEs were comparable to those obtained in Study 1 (Table 3.4). Height was again significantly different between the loading conditions on Day 1 ($F_{3,33}$ = 17.0, $p < 0.001$) and Day 2 ($F_{3,33}$ = 12.7, $p < 0.001$), with participants gaining height after unloading ($p < 0.01$) and losing height between unloading and bowling ($p < 0.01$), as well as between warm-up and bowling on both days ($p < 0.01$).

Table 3.4. Between day stature, typical error (TE) and intraclass correlation (ICC) of Seca 287 measurements (n = 12, bowling).

	Day 1 Stature (cm) Mean±SD	Day 2 Stature (cm) Mean±SD	TE (cm) (95% CI)	ICC (95% CI)
Pre-Unloading	180.3 ±7.6	180.7 ±7.6	0.37 (0.26-0.63)	1.00 (0.99-1.00)
Post-Unloading	180.8 ±7.6	181.1 ±7.6	0.38 (0.27-0.64)	1.00 (0.99-1.00)
Pre-Bowling	180.5 ±7.7	180.8 ±7.7	0.39 (0.27-0.65)	1.00 (0.99-1.00)
Post-Bowling	180.0 ±7.6	180.3 ±7.6	0.46 (0.33-0.79)	1.00 (0.99-1.00)

3.3.3 Study 6

Bland and Altman plots (i.e., difference vs mean) for stature change Pre-Walking (i.e., unloading) and Post-Walking (i.e. loading) are shown in Figures 3.1 and 3.2. The limits of agreement of stature change during unloading demonstrated that measurements from the Seca were 0.52 mm above or 1.14 mm below those obtained from the GSS in 95% of cases. Similarly, after unloading, in 95% of cases, the Seca measurements were 0.71 mm above or 1 mm below those obtained from the GSS. Stature loss during unloading and stature gain during loading were significantly ($p < 0.01$) correlated between the two devices ($r = 0.89$ after unloading and $r = 0.98$ after loading).

Change in height was significantly different between the loading conditions when measured using the Seca 287 ($F_{2,18} = 20.4$, $p < 0.001$), with participants gaining height during unloading (pre-unloading = 168.2±8.2 cm, pre-walking = 168.6±8.1 cm; $p < 0.01$) and losing height after walking (post-walking = 168.0±8.1; $p < 0.01$) in relation to both pre-unloading and pre-walking values.

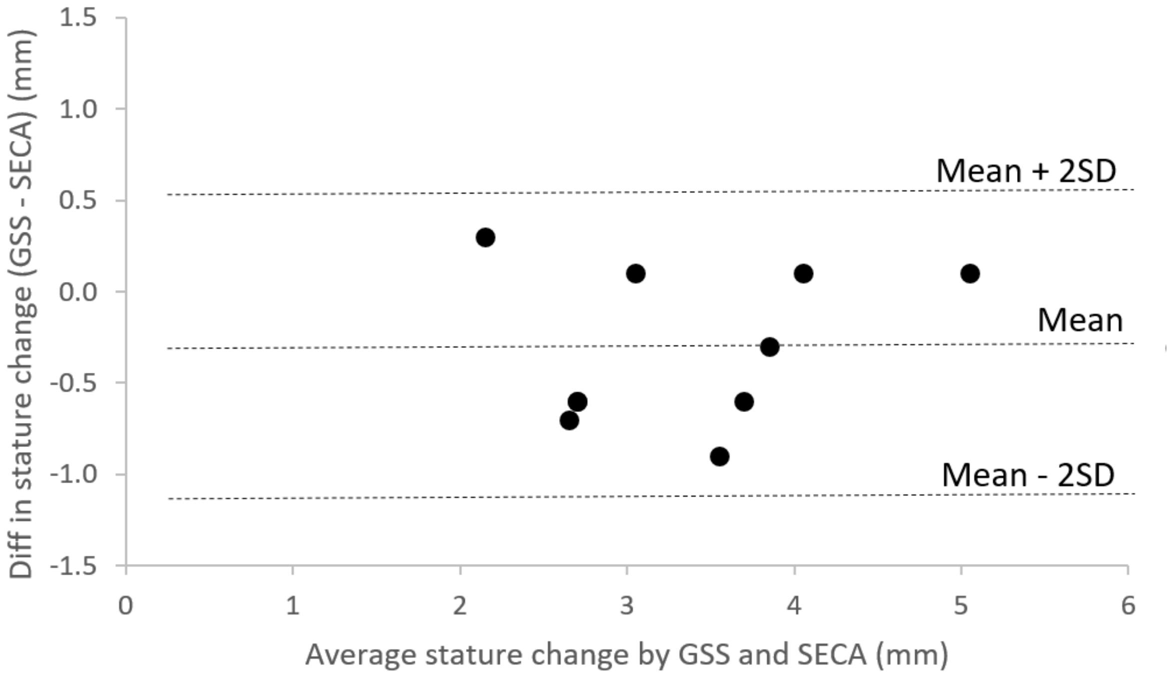


Figure 3.1 Difference against mean stature change measured by the Seca 287 (SECA) and a gold standard stadiometer (GSS) for unloading (limits of agreement shown as mean ± 2 x standard deviation (SD)).

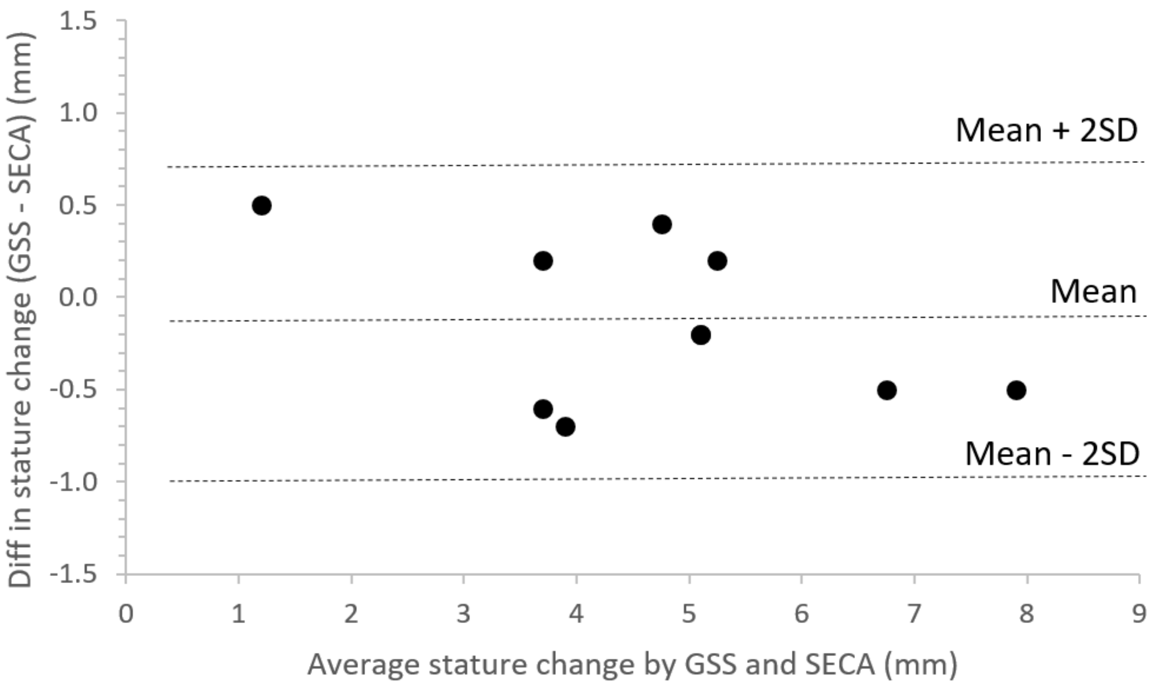


Figure 3.2 Difference against mean stature change measured by the Seca 287 (SECA) and a gold standard stadiometer (GSS) for loading (limits of agreement shown as mean ± 2 x standard deviation (SD)).

3.4 Discussion

Following the examination of the reliability of the custom-built stadiometer for measuring spinal shrinkage in fast bowlers in Chapter 2, the aim of this chapter was to investigate the reliability and validity of the Seca 287 ultrasound stadiometer. Within-day reliability of height was calculated from ten trials that were conducted both before and after participants had walked wearing a weighted vest (Study 4). Between day reliability was assessed by comparing measurements taken on two days before and after both walking (Study 4) and fast bowling (Study 5). To investigate the validity of the Seca 287 stature change measurements taken after walking were compared to those recorded with a custom built, precision stadiometer (Study 6), which was treated as the gold standard. In all three studies, stature change was also compared across loading conditions.

Within-day reliability, i.e. during the same testing session, was excellent with ICCs of 1.00 and TEs between 0.23-0.30 cm when experimenter instructions were used. More specific verbal instruction appeared to improve reliability over the auto instructions, where the TE was 0.42 cm, without significantly altering participants' height. However, this improved reliability only occurred on the first day, as on the second day participants may have remembered the verbal instructions given on Day 1 without the need to hear them again. Reliability values compare favourably with Elia et al. (2019) who reported precision measurements of 0.19 cm in healthy individuals and 0.37 cm in patients when using the Seca 287. The results are also in agreement with intra-rater TEs previously presented by Geeta et al. (2009) (0.32 cm), Ayele et al. (2012) (0.29-0.38 cm), Gomez-Cabello et al., (2012) (<0.25 cm) and De Miguel-Etayo et al., 2014 (0.07-0.2 cm), who used other commercially available stadiometers.

When presented as SDs, with experimenter instructions used, values (0.23-0.28 cm) again compare well to those previously reported (0.26-0.29 cm) (Voss et al., 1990), but are not as low as those presented by Pennell et al. (2012) (0.089 and 0.117 cm). However, Pennell et al.'s (2012) participants were seated with the lumbar and cervical spine supported and care was taken to ensure consistent positioning of their head, which would likely have reduced postural variation between trials. A limitation of the Seca 287 is that it does not easily facilitate spinal support in this way, on the contrary, it requires patients to stand in the device unsupported. This limitation is somewhat diminished, at least for bowling, as measurements in Chapter 2 showed that the curvatures of the spine remained the same after 8 overs of bowling.

Between-day reliability in walking showed ICCs of 1.00 but had slightly higher TEs (0.26 – 0.39 cm) than those recorded from the same participants on a single day. This outcome was expected as participants are likely to have greater variability in how they stand on the Seca 287 between days rather than when they are stepping on and off in quick succession. Cricket bowlers demonstrated slightly higher between-day TEs (0.37-0.46 cm) than walkers, although their ICCs were also 1.00. Bowling/fielding are more strenuous activities than walking and are likely to entail more variable movement and loading patterns. Thus, greater variation in stature would be likely between the two sessions. Moreover, due to the higher intensity of the activity, the cricketers may have found it more difficult to remain in a stationary position on the Seca 287 whilst the measurements were being taken. Using the same device, Elia et al. (2019) found that if participants moved away from the central measuring position (2.5 to 10cm deviation) during measurement, stature could show a difference of 0.3 cm-1.0 cm.

The Seca 287 differs from the less sophisticated commercially available stadiometers in that it does not require the experimenter (or rater) to lower a caliper onto the top of the head before the measurement is taken. Thus, as found by Voss & Bailey (1994) and Mikula et al. (2016), substantial differences in the height of a single patient measured by different raters should not occur when the Seca 287 is used. As rater input should contribute far less to the variability of measurements, this investigation chose, unlike many previous studies, to measure within-day and between-day reliability rather than between-rater reliability. Providing that stadiometers are installed correctly, there should also be very little technical or instrument error that contributes to inflation of reliability statistics (Voss et al., 1990), particularly for the Seca 287 that uses ultrasound sensors rather than a head caliper. Even so, to ensure precision of measurement, Elia et al. (2019) emphasise the importance of maintaining a vertical column and level plate when installing the Seca 287 as was the case in the studies in this Chapter. With correct installation the main source of variability between measures should be due to the patient or participant (Voss et al., 1990). For measurements taken in quick succession, such as those used to calculate within day reliability in Study 4, variability will occur due to subtle changes in patient positioning and posture.

Measurements gathered over a longer period, for example between days as in Study 5, could vary due to minor changes in the height of intervertebral disks as well. Whilst subtle changes in height will always exist between days, as the studies in this chapter suggest, such variation should be minimised with measurements taken at the same time of day to reduce circadian variation (Healey et al., 2008).

The excellent reliability of the Seca 287 for measuring height, particularly on the same day, satisfies one aspect of its validity; the other is the need for the device to measure what it purports to measure. Previous research has evaluated this validity by comparing the known length of a rod with its measured length placed upright in the stadiometer (Voss et al., 1990; Mikula et al., 2016; Elia et al., 2019), or by comparing measurements from one commercially available stadiometer with those from another (Baharudin et al., 2017; Elia et al., 2019). Following the work of Pennell et al. (2012), an additional objective was to ascertain whether the Seca 287 could be used as a surrogate for custom made stadiometers designed to measure small changes in stature due to spinal shrinkage. Thus, this investigation chose to assess concurrent validity of the Seca 287 by comparing its change in measurements with those of a high precision custom made stadiometer. Limits of agreement between the devices were generally less than 1 mm, meaning that measurements from the Seca will generally be within 1 mm of the value recorded by the 'gold standard' stadiometer. Less than or equal to 1 mm tallies with the measurement resolution, or "graduation" presented in marketing material for the Seca 287. There was also, however, a tendency for the Seca to overestimate stature loss by up to one third of a mm, which may vary from one device to another.

Validity was supported by correlation coefficients in excess of 0.89 between stature changes from the two devices, as well as by the ability of the Seca 287 to detect statistically significant gains in height as a result of unloading and loss in height after walking and bowling. All but one of the participants in studies 4 and 6 experienced a reduction in stature after walking, with the magnitude (0.6-0.7 cm) slightly greater than that those reported in the literature of 0.54 cm (Healey et al., 2008). Similarly, bowling caused all but one cricketer to lose height on day 1 and all but two to reduce in stature on day 2, with the mean amount (0.4 cm) being close to the 0.47 cm reported by Barry (2007).

These findings demonstrate that the Seca 287 has face validity, in addition to concurrent validity, and, in agreement with Pennell et al. (2012), indicate that the device could be used to assess spinal shrinkage in clinical situations. Clinicians and scientists etc. wishing to use the device to estimate spinal shrinkage do, however, need to be mindful that the resolution of commercially available stadiometers, including the Seca 287, is only 0.1 cm, whereas custom made devices can often measure to 0.001 cm. Large changes in spinal shrinkage such as those found in fast bowling should be able to be measured using the Seca 287, however the Typical Error of measurements should also be considered when assessing whether change in stature is meaningful from one condition to another. For example, in the case of the smallest TE from walking in Study 4 (0.23 cm), the 95% CIs of a single height measurement of 180 cm are 179.51 to 180.49 cm. This range increases to 178.99 to 181.01 cm when Post-Bowling reliability data from Study 5 (TE = 0.46 cm) is used; with both ranges greater than the change in stature typically observed during walking or bowling. Thus, whilst the findings show that sophisticated commercial stadiometers can detect the relatively large stature changes experienced during walking and bowling, manufacturers need to improve the measurement resolution to 0.01 cm before they can be considered adequate surrogates for custom-built stadiometers. In addition, users should endeavour to reduce their TE to, for example, 0.1 cm, which would reduce the 95% CIs to 2 mm either side of the specified height. Whereas Pennell et al. (2012) managed to achieve SDs that matched those from users of 'gold standard' stadiometers, current results from this investigation, and those from previous research (Voss et al., 2004; Kanlayanaphotporn et al., 2002; Steele et al., 2016), indicate that reducing the TE or SD below 0.2 cm would be difficult during unsupported standing.

Whilst reliability of the Seca 287 was investigated both within and between days in different scenarios, and its concurrent validity assessed against a 'gold standard' device, there were some limitations to the methods. Due to time constraints on the bowlers in Study 5, only one height measurement was taken in each of the conditions on each day, possibly contributing to the higher TEs. Ayele et al. (2012) discovered that taking the median of three measurements, rather than using a single measure or the mean of three values, reduced the TE. The studies in this chapter used relatively low numbers of participants (Study 4 = 16, Study 5 = 12, and Study 6 = 10) in relation to some previous research into the reliability and validity of stadiometry (Geeta et al., 2009; Ayele et al., 2012; Baharudin et al., 2017; Elia et al., 2019). However, the number of participants is greater than or equal to those used in studies that have not been part of larger epidemiological research (Voss et al., 1990; Miguel-Etayo et al., 2014), and the reliability statistics are consistent across those studies for both larger and smaller participant numbers.

3.5 Conclusion

Within- and between-day reliability of height measurements from the Seca 287 was excellent in groups of young walkers and cricket bowlers, and compared very well to the reliability, reported in previous studies, of less sophisticated devices that use a head caliper. The Seca 287 also demonstrated excellent concurrent validity, when compared to a high precision, custom made stadiometer, which was considered the 'gold standard'. The Seca 287 is an appropriate device to estimate relatively large stature changes typically seen during unloading and loading during exercise such as fast bowling. When measuring in the field setting, care must be taken on accurate installation and the participant remaining central in the device during measurement. This, in combination with clear instructions for participants to remain still during measurement, should minimise the typical error so that the Seca 287 can be used to measure spinal shrinkage after activities such as bowling.

Chapter 4 – The relationships between injury risk factors, and lumbar injury in an elite fast bowling squad.

4.1 Introduction

As highlighted in Chapter 1, cricket has led the way in world sport to develop a framework for injury surveillance that aids in reporting the incidence and prevalence of injury (Orchard et al., 2005; Orchard et al., 2016). The extent of the lumbar injury problem among elite fast bowlers has been reported in numerous studies *(*Leary & White, 2000; Orchard et al., 2002; Portus et al., 2004; Ranson et al., 2005; Frost & Chalmers, 2014; Alway et al., 2019; Goggins et al., 2020). The nature of such injury is complex, the result of interaction between many risk factors (Morton et al., 2014; Olivier et al., 2016). As introduced in Chapter 1, previous research in cricket into possible mechanisms associated with the high incidence of injury has tended to be reductionist in nature, focussing on the biomechanics of the bowling action, musculoskeletal measures (muscle strength, flexibility, back muscle asymmetry, hip range of motion, bone mineral density) and workload, all in isolation from one another (Morton et al 2014; Olivier et al., 2016;). Research that has compared these mechanisms together as potential lower back injury risk factors, has focussed on adolescent fast bowlers (Elliott et al.,1992; Bayne et al., 2015).

Spinal shrinkage and lumbar morphology have received minimal attention as risk factors for lumbar injury. Research has shown that amateur bowlers shrink in stature after bowling but no link to injury has been reported (Reilly & Chana 1994; Barry 2007; Study 1 and 3, Chapter 2). More recently, Hecimovich & Stomski (2016) compared lumbar sagittal curvature in junior fast bowlers, including those with a history of low back injury and asymptomatic individuals, with those previously injured displaying a significantly more lordotic curvature. This Chapter will address this gap in the research literature by taking a multifactorial approach to the analysis of spinal shrinkage and lumbar curvature to investigate lower back injury in a group of adult elite fast bowlers.

Aim – To assess the association between internal risk factors and lumbar injury in a group of elite fast bowlers.

Objectives

Document the incidence and prevalence of injuries to an elite fast bowling squad over a full English First-Class county cricket (FCCC) season (2019).

Assess the effect of bowling on spinal curvature and spinal shrinkage.

Establish the biomechanics of the action, as well as fitness and musculoskeletal characteristics of elite fast bowlers.

Examine correlations between spinal shrinkage, lumbar curvature, the biomechanics of the action, fitness and musculoskeletal screening scores.

Explore the retrospective associations between spinal shrinkage and curvature, bowling biomechanics, fitness and musculoskeletal parameters with injuries to fast bowlers during a full season.

4.2 Methods – Study 7

4.2.1 Preamble

During the 2020 pre-season of a FCCC squad, stature changes and upright sagittal lumbar curvature were measured in elite bowlers after five overs of bowling. Other assessments included fitness, musculoskeletal function and the biomechanics of each bowler's action using 3D video. Details on injuries sustained by the same bowlers during the previous season were obtained using definitions from the International consensus statement on injury surveillance in cricket (Orchard et al., 2016). Ethical approval was received from the Manchester Metropolitan University Research Ethics Committee.

4.2.2 Participants

Fourteen elite fast bowlers (three left-arm and 11 right-arm) belonging to an English FCCC squad, volunteered for the study. Participants had a mean age 25 (±5.2) years, with a mean height of 184.9 (±8.2) cm and mean body mass 81.42 (±10.25) kg. To be included in the study, all participants had reported no previous or current spinal injuries which required hospitalisation or consultation with a physician within the four months prior to testing. Any bowler whom an elite wicketkeeper would normally stand back to were defined as fast and all bowlers were deemed fit to bowl by a chartered physiotherapist (Alway et al., 2020).

Participants were fully briefed about the procedures prior to the commencement of any testing and were given the opportunity to ask any questions after reading the participant information sheets (see Appendix 1). Written informed consent was obtained from all participants (see Appendix 2). Fitness and musculoskeletal testing were part of the county medical team's approach to screening players and agreement for these procedures and results to be shared were given by the county medical staff.

4.2.3 Injury surveillance

Permission was given by bowlers and medical staff to analyse retrospective injury surveillance data from the FCCC squad from January 1st – December 31st, 2019. Match, seasonal and annual injury incidence rates were calculated using the internationally agreed methods for elite cricketers (Orchard et al., 2016). During the 183-day season, 91 match days were recorded for the squad. Bowling one ball equated to a single delivery and six balls equated to an over. New and recurrent injuries were classified by the county medical staff for the lower back according to Orchard's Sports Injury and Illness Classification System (OSIICS) (Orchard et al. 2020). These included lumbar spine muscle and tendon strain and lumbar facet joint pain, stiffness, and ligament sprain (Orchard et al., 2020). Lumbar disc injury and/or stress fracture was recorded if diagnosis was corroborated by MRI and/or CT scan which assessed acute bone stress changes associated with partial or complete fracture of the posterior elements of the lumbar spine (Ranson et al., 2010).

To allow for comparison to previous research from England and Australia (Goggins et al., 2020; Orchard et al., 2020), new and recurrent injuries were reported as match incidence, relative to 1000 match days, 10 000 deliveries and 1000 overs bowled, as follows:

Match Incidence = injuries/total match days x 1000 match days

injuries/total match day season deliveries x 10 000 deliveries

injuries/total match day season overs x 1000 overs

Annual injury incidence accounted for the temporal exposure of a 365-day calendar year (Orchard et al., 2016) whereas seasonal incidence was considered over 183 days, as follows. The size of the squad was taken at 100 players to enable calculation of the number of injuries per 100 players per year:

Annual Incidence = injuries/27 squad players x 100 players

Seasonal Incidence = injuries/27 squad players x 100 players

Annual injury prevalence measures, presented as a percentage, were defined as the number of squad players unavailable for selection, the number of bowlers unavailable for selection, and the number of bowlers who sustained a lumbar injury and were unavailable for selection over a 365-day period (Orchard et al., 2016) i.e,:-

(missed player days / 365 x the number of squad members) x 100

4.2.4 Spinal shrinkage and curvature protocol

All stature and curvature measurements were taken on the same day during pre-season preparation between 11:00-15:00 hrs. On arrival at the indoor cricket centre bowlers had their stature measured three times by the Seca 287 sonic stadiometer (Secagmbh, Hamburg, Germany). The median of three values was recorded to reduce the Typical Error (Ayele et al., 2012). Further measurements of stature were taken, first following 20 minutes unloading in the Fowler position, then after a 15-minute warm-up, and finally on completion of five overs of bowling using a full run-up. For each measurement, the protocol from Study 4 (Chapter 3 – Methods 3.2) was adopted incluidng detailed instructions by the experimenter to "stand on the specific marks placed on the platform to align your heels and toes, keep both feet shoulder width apart, lock knees, relax shoulders, look straight forward and hold your breath after inhalation."

Lumbar curvature measurements were taken using the Spinal Mouse (Idiag, Volkerswill, Switzerland) for the upright position in the sagittal plane prior to bowling and on completion of five overs. The measurement protocol from Studies 1 and 2 in Chapter 2 (Methods 2.2.3) was followed.

4.2.5 Biomechanical analysis

4.2.5.1 Data capture

On separate days within the pre-season, and no more than two weeks before or after spinal measurements were taken, bowlers were filmed bowling one over for biomechanical analysis. Three POI (GigE) cameras (Stemmer Imaging, Mako G-223B, Surrey, UK), with KOWA fixed focal length lenses (12.5 mm / F1.4) and full HD resolution (2048-x-1088-px) were used to record deliveries. The cameras were connected to the controlling computer through high-speed transfer Ethernet cables sampling at 50Hz. The optical axis of each camera allowed a clear view of the bowler during the delivery stride (see Figure 4.1). A 24-point three-dimensional calibration frame (1.306m (X) x 2.095m (Y) x 2.062m (Z)) was filmed in the performance space before the start of bowling (see Figure 4.2). Synchronisation of cameras was obtained through recording software (Gecko GigE video recorder v1.9.4, Vision Experts Ltd, Surrey, England).

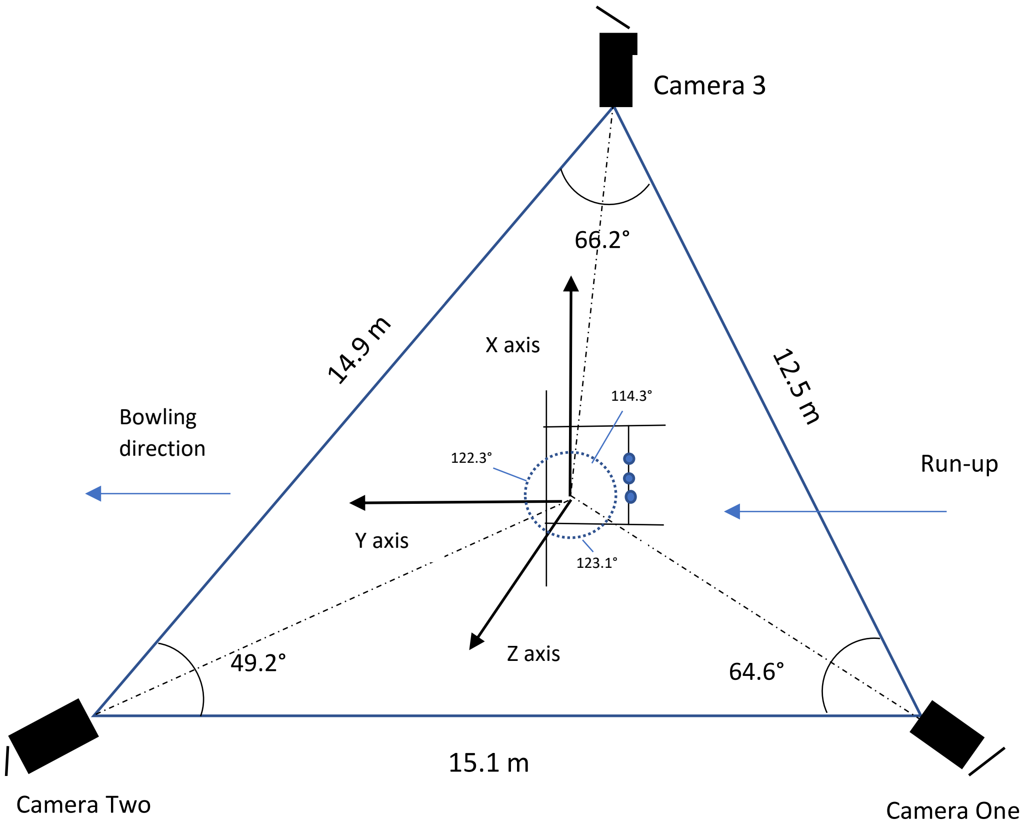


Figure 4.1 Camera positioning at the indoor cricket centre

Figure 4.2 Calibration frame

Three-dimensional kinematic data for 10 fast bowlers (four were unable to be filmed due to International duty and subsequent suspension of activities in the wake of the Covid-19 pandemic) was collected in a well-lit indoor cricket centre containing a full-length artificial pitch with space for a full run-up. Bowlers conducted their own warm-up, and the 5th delivery of the over was chosen for analysis.

4.2.5.2 Data reduction

Utilising the SIMI 8.55 motion analysis system (Simi Reality Motion Systems, Gmbh, Unterscleissheim, Germany), a manual process for joint centre estimation was applied for the purpose of digitising all deliveries. The right and left metatarsal phalangeal joints of the foot, and the left and right ankle, knee, hip, and shoulder joint centres as well as the cricket ball were digitised for each frame of the three camera views. A seven-segment model (trunk; upper leg (left and right); lower leg (left and right); and foot (left and right) was estimated by joining a line between the joint centres, apart from the trunk which was represented by a line between the mid-point of the hip and shoulder segments. Analysis started 10 frames before back-foot impact to be able to estimate run-up speed, and ended when the ball left the first image, approximately four frames after ball release.

Digitised coordinates were smoothed with a second order low pass Butterworth filter, with a cut-off frequency of 6 Hz determined from analysis of the residual difference between the raw and filtered data calculated in an Excel spreadsheet (Winter, 1990). Smoothed co-ordinates from the three 2D views were transformed into 3D co-ordinates by means of a direct linear transformation (DLT) procedure first described by Abdel-Aziz & Karara (1971). As shown in Figure 4.1 the global coordinate system was defined by the positive Y-axis pointed down the wicket, the positive X-axis to the bowlers right, and the positive Z-axis pointing vertically upwards (Portus et al., 2004; Worthington et al., 2013; Alway et al., 2020). Back foot contact (BFC) and front foot contact (FFC) were identified as the first image when the right and then the left foot (for a right-arm bowler) entered into full contact with the ground during the delivery, whilst ball release (BR) was identified as the first frame after the ball left the bowler's hand (see Figure 4.3).

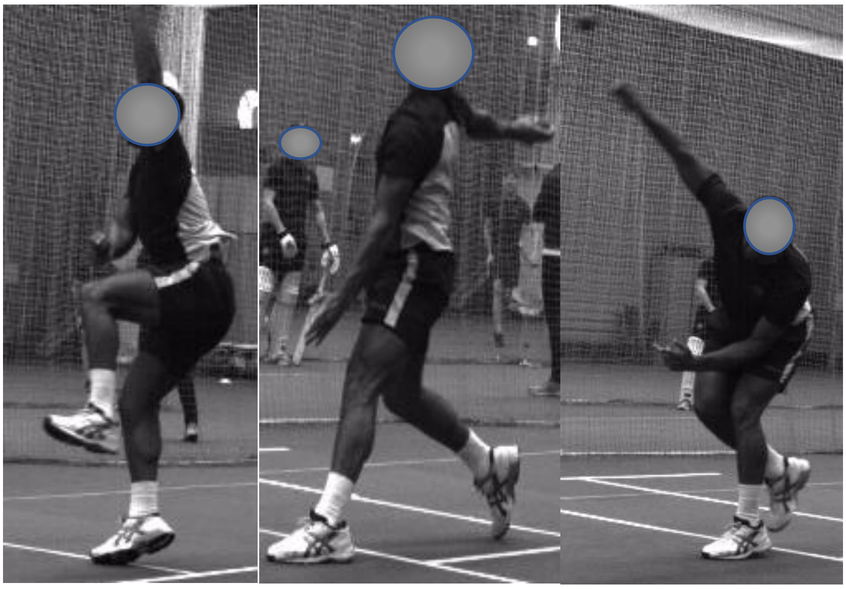


Figure 4.3 Bowler at back foot contact (BFC), front foot contact (FFC) and ball release (BR) from 3 camera angles

4.2.5.3 Data Analysis

The biomechanical variables measured during the bowling action were selected from previous research that highlighted potential risk factors associated with the bowling action (Portus et al., 2004; Worthington et al., 2013; Alway et al., 2020) and are defined in Table 4.1. The reliability of the digitisation process was assessed using the coefficient of variation (CV) of each biomechanical variable (see Table 4.1) from three digitisations of the same delivery. The mean CV of 10.8% (range 0.4-36%) compared favourably with previous research using joint centre estimation (Salo & Grimshaw 1998).

4.2.5.4 Classification of bowling action

The classification of the bowling action used in this study, with reference to both shoulder and hip twist angles are shown in Figure 4.4 and described in Table 4.1. (Portus et al., 2004). As highlighted in Chapter 1, four distinct bowling actions have been reported: the side-on, front-on, semi-open and mixed actions have been described in the literature (Burnett et al., 1995; Foster and Elliot, 1989; Bartlett et al., 1996; Portus et al., 2004). These classifications have been used in previous research to critique the relationship of variables describing the action to lower back injury and are as follows (Ranson, et al., 2008; Ferdinands et al.,2009; Crewe et al.,2012).

Side-on: a shoulder segment angle less than 210° at back foot contact, a hip-shoulder separation angle less than 30° at back foot contact, and, shoulder counter-rotation less than 30°.

Semi-open: a shoulder segment angle from 210 to 240° at back foot contact, a hip-shoulder separation angle less than 30° at back foot contact, and, shoulder counter-rotation less than 30°.

Front-on: a shoulder segment angle greater than 240° at back foot contact, a hip-shoulder separation angle less than 30° at back foot contact, and, shoulder counter-rotation less than 30°.

Mixed: a hip-shoulder separation angle equal to or greater than 30° at back foot contact, or, shoulder counter-rotation equal to or greater than 30°.

The role of the front leg during FFC has been implicated as a potential risk in lower back injury (Foster et al., 1989; Portus et al., 2004). The classification criterion of front lower limb actions during FFC used in this study was based on the work of Portus et al. (2004) as set out below (see Table 4.1).

Flexor: knee flexion 10° or more followed by less than 10° of knee extension.

Flexor-extender: flexion and extension of the knee by 10° or more.

Extender: knee flexion less than 10° followed by knee extension by 10° or more.

Constant brace: both flexion and extension of the knee less than 10°.

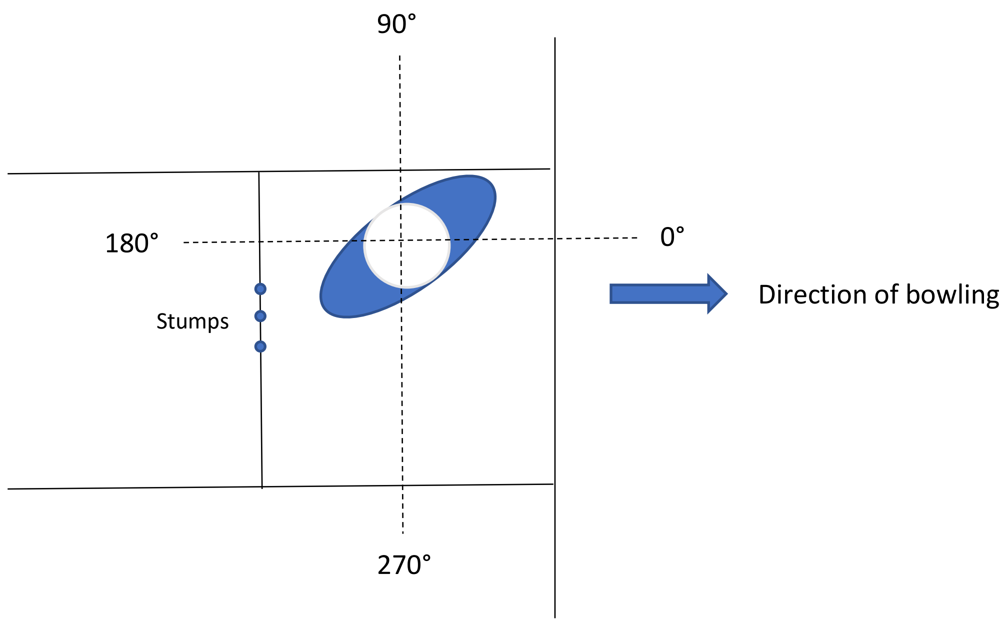


Figure 4.4 Angle of hip and shoulder twist used in classifying the action of a right-armed bowler (adapted from Portus et al. (2004).

Table 4.1 Biomechanical data analysis

Name	Unit of Measur-ement	When the measurement was taken	How it was obtained
Run-up velocity	$m \cdot s^{-1}$	BFC	Measured as the mean of the velocity of the mid-point of the right and left hip (in the global y-direction) over a period of 10 frames (0.2 s) immediately before BFC.
Shoulder orientation - twist	degrees	BFC and FFC	The angle of the line joining the shoulders in the XZ plane, as defined by Alway et al., (2020) (see Figure 4.4 for angle convention)
Pelvis-shoulder separation	degrees	BFC	The subtraction of the pelvis twist from the shoulder twist orientation at BFC, as defined by Portus et al. (2004).
Shoulder counter-rotation	degrees	Between BFC and BR	The subtraction of the minimum shoulder twist during the delivery stride (BFC to BR) from shoulder twist orientation at BFC, as defined by Portus et al. (2004).
Rear knee	degrees	BFC	Relative angle of between upper and lower leg segments (right side for right-handed bowler). 180° = fully extended
Rear knee minimum	degrees	Between BFC and BR	Smallest angle during the delivery stride (BFC to BR)
Rear knee collapse	degrees	Between BFC and BR	Subtraction of the rear knee angle at BFC contact from the rear knee minimum angle.
Front knee	degrees	FFC	Relative angle between upper and lower leg segments (left side for right-handed bowler). 180° = fully extended.
Front knee minimum	degrees	Between BFC and BR	Smallest angle during delivery stride (BFC to BR) equating to maximum flexion of the knee.
Front knee extension	degrees	FFC to BR	Subtraction of the angle at BR from largest knee flexion angle during delivery stride (Portus et al., 2004).
Rear hip	degrees	BFC	Relative angle between trunk and upper leg segments (right side for right-handed bowler). 180° = fully extended.
Front hip	degrees	FFC	Relative angle between trunk and upper leg segments (right side for right-hand bowler).
Front leg plant	degrees	FFC	The angle between a vertical line and the line between the hip joint and the ankle joint in relation to the XY plane, as defined by Worthington et al. (2013).
Pelvis-drop	degrees	At BFC, FFC & BR	The angle was determined relative to the anatomical position (180°) and the bowling side in relation to the XY plane with contralateral drop below 180°, as defined by Alway et al. (2020).
Pelvis-twist	degrees	At BFC, FFC & BR	The angle was determined relative to the anatomical position (180°) and the bowling side in relation to the XZ plane, with contralateral twist below 180°, as defined by Alway et al. (2020).
Lateral spine flexion	degrees	BR	The angle of the line between mid-shoulder and mid hip in relation to the XZ plane at BR, when the pelvis was close to 0° degrees within the same plane. Negative angles indicated lateral flexion to the contralateral side.

BFC = back foot contact; FFC = front foot contact; BR = ball release.

4.2.6 Fitness and Musculoskeletal tests

The selected fitness and musculoskeletal screening tests were drawn from common screening protocols used in cricket and elite sport (Elliott et al., 1992; Dennis et al., 2008; Bayne et al., 2015). Testing procedures were adopted from previously published methods as outlined in Table 4.2. All fitness testing and musculoskeletal screening were conducted over a two-week period by the head strength and conditioning coach and lead physiotherapist respectively to enhance reliability (Dennis et al., 2008). The tests conducted were part of the FCCC squad's normal assessment procedures. All bowlers were familiar with the tests to minimise any learning effects and were asked to abstain from strenuous activity for 48 hours before testing. Previous research with a similar population had shown good relative and absolute reliability for all body composition measurements, sprint and countermovement jump tests (Webster et al., 2020).

Table 4.2 Fitness testing and musculoskeletal screening protocol

Test	Protocol
Skinfolds	The sum of 8 skinfolds were taken from the biceps, triceps, subscapular, abdominal, iliac crest, supraspinale, mid-thigh and mid-calf regions using Harpenden skinfold callipers (model C-136) and the mean of 3 measurements recorded in mm (Heyward et al., 2004).
Countermovement jump (CMJ)	Jump height (JH) was calculated as $9.81 \times FT^2 /8$, where FT equalled flight time using a KMS jump mat (Fitness Technology, Adelaide, Australia). Ensuring hands were kept on hips, to eliminate arm swing served to standardise the jumps; trials where participants flexed their knees whilst in flight were disregarded. The best of three jumps was recorded in cm (Foden et al., 2015).
Sprint	The fastest of 3 x 20 and 40 metre maximal sprint times were recorded using Brower timing gates (Brower Timing Systems, Draper, Utah, USA). Gates were placed at 20 and 40 m at a height of 1.2 m. Each sprint started 0.3 m behind the start line, to trigger the first gate. A standing start was used, with free choice of front leg in this stance (Lockie et al., 2013).
Maximum aerobic speed (MAS)	Brower timing gates were used to record times for a 2 km maximal run on a 400 m outdoor artificial tartan athletics track. MAS ($m \cdot s^{-1}$) was calculated as distance in metres divided by time in seconds (Berthon et al., 1997)
Run-Two	Time to complete a run two in cricket used Brower timing gates placed at the start of a 17.68m (i.e., length of the pitch) track in the indoor cricket centre. A cricket bat was carried and slid over the batting crease at the opposite end before turning to complete the second run. Particpants initiated the sprint using a two-point standing start 0.3 m behind the first timing gate whilst holding the bat below hip height (Foden et al., 2015). The fastest time of three trial was recorded.
Push-pull ratio	Maximum number of press-ups and modified pull-ups completed in one minute were counted. The former was divided by the latter to obtain the push-pull ratio. The press-up started with elbows fully extended, hands shoulder width apart and the trunk held in a rigid straight position. As the body descended toward the ground, elbows were flexed until the upper arm was parallel to the testing surface. For the pull-up the bar was positioned approximately 8 cm out of arms reach when the bowler was supine on the floor and arms vertical. The bowler had to pull-up until his chest touched the bar, with heels on the floor and an overhand grip was used to grasp the bar (Negrete et al., 2013).
Core stability - planks	The trunk was raised from the ground, with weight taken on forearms and toes in the prone position, elbows flexed at 90° and a neutral spine and pelvis alignment maintained. The length of time (s) the position could be maintained was recorded with the test ending after 120 seconds (Dennis et al., 2008).
Single leg bridge – lower 45-rpm	In the supine position, both knees were flexed at 90°. The hips were raised off the floor so that there was alignment between the shoulder, hip, and knee, with arms extended to the vertical. One foot was lifted off the floor and the knee fully extended. The hips were lowered in time to a beat of 45 repetitions per minute. The number of repetitions was recorded. The test was stopped after 1 minute or if the pelvis began tilting or the back arching. The test conducted for both legs.

Ankle Dorsiflexion	The foot was positioned beside a tape measure with heel and big toe aligned facing a wall. The foot was held to prevent heel lifting and maintain the subtalar joint in neutral. The bowler performed a lunge forward until the knee touched the wall, with the maximum distance achieved from toe to the wall recorded in cm for both ankles (Olivier et al., 2015).
Single leg squat	Standing on one leg, with arms across chest and with the non-weight bearing leg flexed at the knee, 3 squats were repeated attempting to reach 90° knee flexion with the trunk upright. Rank measures of trunk flexion and pelvis lateral tilt were measured with movement categories noted as none (=1), mild (=2), moderate (=3) and severe (=4). Knee valgus and varus of the weight-bearing leg were also noted (Ressman et al., 2019).
Foot arch	Foot types were determined by a physiotherapist observing specific static morphologic features, which included rectus (well aligned hindfoot/forefoot), planus (low arched), and cavus (high arched) classifications (Kruger et al., 2019).
Single leg calf raise	Participants stood on the ball of the foot with forefoot horizontal on a Reebok step, the ankle was plantarflexed as much as possible and then lowered to the horizontal while maintaining a fully extended knee. The number of raises completed in one minute was recorded (Dennis et al., 2008).
Hamstring ROM	The passive straight leg raise test was conducted whilst the participant was in the supine position. The measured leg raised passively by the physiotherapist to the end of range, at which point, the angle was measured in relation to the horizontal. ROM was obtained using an digital goniometer placed on the shin. Both hips remained in contact with the bed during measurement (Shacklock 2005).
Hip strength and ROM – tensor fascia latae (TFL), gluteus medius (GMed), quadraceps.	Side lying with the bottom knee and hip flexed to flatten the lumbar curve was the start position for both the TFL and GMed tests. The Ober test was undertaken to test TFL function, where the hip was held firmly, and the upper leg was flexed to 90°. The physiotherapist extended and abducted the hip joint and then lowered the leg towards the table until motion was restricted. The straight upper leg was similarly abducted and extended to conduct the GMed test. Both tests were graded on a 5-point Likert scale from restricted (1) to feely movable (5). Quadriceps ROM was measured in prone lying with the distance from the gluteus maximus to the calcaneus recorded in cm after full flexion of the knee.

ROM = range of movement; rpm = repetitions per minute

4.2.7 Statistical analysis

The normality of all continuous data was examined using the Shapiro-Wilk test. Where data were not normally distributed, or categorical in nature, non-parametric statistical tests were conducted. A One-Way Repeated Measures Analysis of Variance (ANOVA) was conducted to compare the effect on spinal shrinkage of bowling five overs. Mauchly's test of sphericity was applied where appropriate. Paired sample t-tests were used to analyse the effect of bowling on curvature with statistical significance set to $p < 0.05$.

Pearson's Product Moment correlation coefficients were used to examine the associations between spinal shrinkage, curvature, and stature. Associations between all fitness, musculoskeletal scores and spinal shrinkage and curvature were also determined through the application of Pearson's correlation for interval/ratio level data that was deemed to be normally distributed, and Spearman's Rank order correlation for categorically ranked data.

The fast bowlers were separated into those who sustained a lumbar stress injury in the 2019 season and those who did not according to Orchard's Sports Injury and Illness Classification System (OSIICS) (Orchard et al. 2020). Since there was a violation of normality of distribution, due to the relatively small numbers of bowlers who became injured, a Mann-Whitney U test was used to compare the injured and uninjured participants for all variables. Partial eta^2 was used to calculate the effect sizes for the One-Way Repeated measures ANOVA. Cohen's d and r for the paired sample t-tests and Mann-Whitney U test, respectively. Cohen's r effect size was reported with 0.1 = small, 0.3 = medium and 0. 5 = large (Coolican, 2009, p. 395; Firitz et al., 2012). The assumption of the similarity of distribution of the dependent variable by group was not met and thus mean ranks rather than medians were summarised (Hart 2001).

4.3 Results

4.3.1 Injury incidence

The 14 bowlers were part of a squad of 27 players in 2019. They played 91 days of cricket during the season consisting of 13 one-day 50 over matches, 18 20-over games and 15 county championship 4-day games. In table 4.3 annual, seasonal and match injury incidence along with annual injury prevalence are presented for the squad, and the fast bowlers for all injuries obtained during bowling as well as specific lumbar injuries. Those bowlers who sustained lumbar injuries were assessed as having spine muscle and/or tendon strain and lumbar facet joint pain (Orchard et al., 2020).

Table 4.3 – Annual, seasonal and match injury incidence and annual prevalence for an elite cricket squad

		Fast bowlers (n =14)		
	Squad injuries	All injuries	Bowling injuries	Lumbar Injuries
Match incidence injuries per 1000 player days	362.6	109.9	87.9	22.0
Match incidence injuries per 10000 deliveries	n/a	2.4	1.9	0.5
Match incidence injuries per 1000 overs	n/a	1.4	1.2	0.3
Annual incidence per 100 players	240.7	118.5	77.8	7.4
Seasonal incidence per 100 players	122.2	59.3	33.3	7.4
Annual incidence per 100 bowlers	n/a	228.6	150.0	14.3
Seasonal incidence per 100 bowlers	n/a	114.3	57.1	14.3
Annual injury prevalence a %	10.9	7.0	n/a	0.63

4.3.2 Stature, spinal shrinkage, and curvature

A statistically significant main effect was found for bowling on spinal shrinkage ($F_{3,39} = 10.24$, $p < 0.001$, η^2 0.44) (see Figure 4.5). Bonferroni post hoc tests showed a significant gain in stature between the on arrival and unloaded conditions (4 mm; 95% CI 1-7 mm), thereafter a significant loss in height (i.e., shrinkage) was found after the warm-up (3 mm; 95% CI 1-5 mm) and the 5th over (5mm; 95% CI 2-8mm) (p< 0.001). Spinal shrinkage was significantly greater in bowlers who sustained a lumbar injury (U = ($N_{injured}$ = 3, $N_{not-injured}$ = 11) 3.00, p = 0.033, r = .56) (see Table 4.5) although there was no significant correlation between shrinkage and stature.

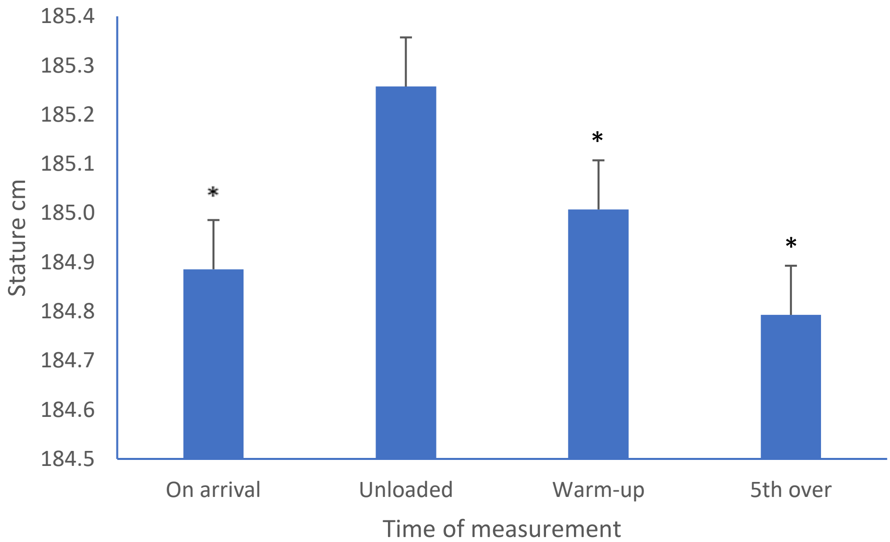


Figure 4.5 Mean (±SD) spinal shrinkage after warm-up and bowling (* indicate significant difference to unloaded measure p< 0.05).

Table 4.4 Curvature before and after 5 overs of fast bowling (all bowlers n=14)

	Lumbar lordosis Pre- Unloading	Lumbar lordosis After 5 overs
mean	26.1°	26.0°
SD	6.0°	6.9°

Table 4.5 – Mean (±SD) spinal shrinkage and lumbar curvature of bowlers who did and did not experience a lumbar spine injury during the 2019 season.

	Injured (n = 3)	Not injured (n=11)
Stature unloaded (cm)	192.4 (0.4)	182.8 (7.7)
Spinal shrinkage (mm)	8 (1)*	4 (3)*
Lumbar lordosis unloaded °	31 (2)	25 (6)

* significant difference p≤ .05

Thirteen bowlers were categorised as having a neutral lumbar lordosis (20° - 40°; Minarro et al., 2017) and the other one as hypolordotic (< 20°). There was no significant change in curvature after five overs of bowling (see Table 4.4) and no significant correlations were found between the shrinkage and curvature. Lumbar lordosis prior to bowling (unloaded) was not found to be significantly different between injured and non-injured bowlers despite a large effect size (U = ($N_{injured}$ = 3, $N_{not-injured}$ = 11) 5.00, p= .072, r = 0.50) (see Table 4.5).

4.3.3 Biomechanics of the action

The biomechanical variables are reported for all bowlers together, as well as those that were injured and not injured (see Table 4.6). Nine of the ten bowlers who were filmed had bowling actions that were classified as mixed, and one bowler was in the front-on category (see Table 4.6). Analysis of front leg parameters at FFC showed that 30% of bowlers were flexors, 40% extenders and 30% were classified has having a constant-brace (Portus et al., 2004). No statistically significant differences were found for any of the biomechanical parameters of the bowling action when comparing injured with injury free bowlers (see Table 4.6).

Analysis of associations between stature change after bowling and the biomechanical parameters of the bowling action highlighted a significant negative correlation between shrinkage and rear knee angle at BFC (r (10) -.85, p = 0.01) and with rear knee collapse (r (10) .66, p = 0.03). A further significant negative correlation was found between spinal shrinkage and front hip angle at FFC (r (10) -.83, p = 0.01). Spinal shrinkage and pelvis-drop demonstrated significant positive correlations at BFC (r (10) .69, p = 0.03) and FFC (r (10) .71, p = 0.02) (see Table 4.6).

Table 4.6 Mean (±SD) biomechanical parameters of bowlers who did and did not experience a lumbar spine injury during the 2019 season.

	Injury group (n=3)				Non-injury group (n=7)				All bowlers			
	BFC	FFC	BR	Delivery	BFC	FFC	BR	Delivery	BFC	FFC	BR	Delivery
Hip velocity BFC ($m \cdot s^{-1}$)	5.19 (0.05)				4.85 (0.51)				5.02 (0.25)			
Shoulder orientation -twist (°)	247 (6)	208 (9)			254 (8)	204 (6)			252 (8)	205 (7)		
Pelvis-shoulder separation (°)	25 (1)				34 (12)				32 (11)			
Shoulder counter-rotation (°)				42 (18)				52 (10)				50 (12)
Rear knee (°)	138 (6)				142 (9)				141 (8)*			
Rear knee minimum (°)				112 (4)				116 (7)	115 (7)			
Rear knee collapse (°)				26 (9)				27 (12)				26 (11)*
Rear hip (°)	139 (2)				132 (18)				133 (17)			
Front knee (°)		169 (3)	164 (14)			166 (7)	168 (16)			166 (6)	167 (16)	
Front knee minimum (°)				165 (12)				162 (15)				163 (14)
Front knee extension (°)		3 (3)				8 (7)				7 (7)		
Front hip (°)		112 (2)				117 (7)				116 (7)*		
Front leg plant (°)		43 (1)				39 (4)				40 (4)		
Pelvis-drop (°)	189 (0)	170 (0)	170 (0)		203 (13)	176 (6)	172 (5)		208 (15)	175 (6)	171 (5)	
Pelvis-twist (°)	226 (5)	202 (3)	176 (2)		230 (17)	219 (17)	177 (7)		229 (16)	215 (17)	177 (7)	
Lateral spine flexion (°)			-39 (14)					-38 (15)				- 38 (15)

* significant correlation with spinal shrinkage; BFC = back foot contact; FFC = Front foot contact; BR = ball release

4.3.4 Fitness tests and musculoskeletal screening

Fitness test and musculoskeletal results are presented for all bowlers together and those sustaining an injury and those not injured (see Table 4.7). No statistically significant differences were found between right/left and dominant/non-dominant musculoskeletal measurements (see Tables 4.7).

Table 4.7 – Mean (±SD) fitness and musculoskeletal parameters of all bowlers and those who did and did not experience a lumbar spine injury during the 2019 season.

	Injured (n = 3)	Not injured (n = 11)	All Bowlers (n= 14)
Skinfold (mm)	77 (11)	69 (12)	71 (12)
CMJ (cm)	39.7 (2.9)	44.7 (4.9)	43.4 (5.2)
20 m sprint (secs)	3.0 (0.1)	2.9 (0.1)	2.9 (0.1)
40 m sprint (secs)	5.5 (0.3)	5.3 (0.2)	5.3 (0.2)
2 km run (mins)	7.8 (0.6)	7.6 (0.7)	7.7 (0.7)
MAS ($m \cdot s^{-1}$)	4.1 (0.3)	4.3 (0.3)	4.2 (0.3)
Run 2 (s)	6.5 (0.2)	6.1 (0.3)	6.2 (0.3)
Press-ups (total)	28 (4.2)	31.5 (7.2)	31 (6.9)
Pull -ups (total)	19 (1,9)	23 (4.9)	22 (4.7)
Push -pull ratio	1.5 (0.1)	1.5 (0.4)	1.5 (0.3)
Plank (s)	120 (0)	120 (0)	120 (0)
Dorsiflexion right ankle (cm)	14 (0.4)	12 (4.1)	12.4 (3.7)
Dorsiflexion left ankle (cm)	13.3 (0.6)	12.5 (4.0)	12.6 (3.6)
Hamstring right leg (degrees)	98.7 (1.9)*	89.5 (5.1)*	91.4 (5.9)
Hamstring left leg (degrees)	97.0 (1.4)*	90.2 (5.5)*	91.6 95.7)
Hip to bottom - right (cm)	-1.0 (1.4)	-0.4 (0.6)	-0.5 (0.9)
Hip to bottom – left (cm)	-0.7 (0.9)	-0.4 (0.9)	- 0.4 (0.9)
Ober test non-dom (1-5)	5.0 (0)	4.9 (0.3)	4.9 (0.3)
Ober test dom (1-5)	5.0 (0)	4.9 (0.3)	4.9 (0.3)
Gluteus medius non-dom (1-5)	5.0 (0)	4.9 (0.3)	4.9 (0.3)
Gluteus medius dom (1-5)	5.0 (0)	4.9 (0.3)	4.9 (0.3)
Single leg squat (1-4)			
Trunk flexion non-dom	2.0 (0)	2.6 (0.6)	2.5 (0.6)
Trunk flexion dom	2.0 (0)	2.5 (0.5)	2.4 (0.5)
Pelvis lateral tilt non-dom	1.3 (0.5)	1.5 (0.7)	1.4 (0.6)**
Pelvis lateral tilt dom	1.0 (0)	1.3 (0.4)	1.2 (0.4)**
Single leg calf raise – right (total)	25.7 (3.3)	26.0 (3.4)	25.9 (3.4)
Single leg calf raise – left (total)	26.0 (2.9)	25.9 (3.7)	25.9 (3.5)
Single leg bridge – right (total)	32.7 (2.5)	34.4 (7.9)	34 (7.1)
Single leg bridge – left (total)	32.0 (1.6)	33.4 (8.7)	33.1 (7.8)

dom = dominant leg; non-dom = non dominant leg; 1-5 = Likert scale 1 = severe stiffness, 2 = moderate stiffness, 3 = mild stiffness, 4 = end range stiffness 5 = freely movable; 1-4 Likert scale 1 = none, 2 = mild, 3 = moderate, 4 = severe;
* = significant difference $p < .05$; ** = significant correlation with spinal shrinkage.

Injured bowlers demonstrated greater hamstring flexibility on both legs compared to those who were injury free and this was statistically significant. Large effect sizes were found for both the right side (U = $N_{injured}$ = 3, $N_{not\text{-}injured}$ = 11, p = .012, r = 0.67) and left side (U = ($N_{injured}$ = 3, $N_{not\text{-}injured}$ = 11, p = 0.034, r = 0.57) (see Table 4.7). Knee valgus was present in 29% of the bowlers in the single leg squat but no significant difference was observed between injured and non-injured bowlers.

A significant negative correlation between spinal shrinkage and pelvic tilt was reported for both dominant and non-dominant legs (non-dom - r_s (14) -0.58, p = .03; dom - r_s (14) -.57, p = 0.03) (see Table 4.7). No other statistically significant correlations were observed between spinal shrinkage and other fitness and musculoskeletal parameters. Similarly, no significant associations were observed between lumbar lordosis and fitness or musculoskeletal measurements.

4.4 Discussion

This chapter has assessed the associations a range of different risk factors and lumbar injury in a group of elite fast bowlers. To aid the consideration of each objective, sub-sections will be used throughout the discussion.

4.4.1 Injury

The incidence and prevalence of injury to an elite fast bowling squad over a full English FCCC season (2019) has been analysed. A match injury incidence of 87.9 for bowling per 1000 player days was higher than the results of both Goggins et al. (2020) (41.6) and Orchard et al. (2010) (61.4). Similarly, match incidence, during bowling, of lumbar injuries per 100 player days was more than double that reported by Goggins et al. (2020) although seasonal lumbar injury incidence per 100 players was similar (see Table 4.3). In keeping with Orchard et al. (2010) further evidence of the injury cost of bowling is apparent in a match incidence of 1.5 injuries per 1000 overs bowled. These results also support previous research demonstrating that elite fast bowlers experience a high injury incidence (Leary & White, 2000; Orchard et al., 2002; Portus et al., 2004; Ranson et al., 2005; Frost & Chalmers, 2014; Alway et al., 2019; Goggins et al., 2020).

Although annual injury prevalence for the whole squad was higher than in previous research (Goggins et al.,2020; Orchard et al., 2010), annual injury prevalence for lumbar spine injury in fast bowlers was less than the 1.35% and 0.83% reported by Goggins et al. (2020) and Orchard et al (2010) respectively. The discrepancy owes largely to the fact that none of the bowlers in the current study suffered a stress fracture of the spine in the 2019 season. Moreover, this specific injury has been shown to lead to a significantly longer absence from playing when compared to general lumbar injuries (Orchard et al., 2016).

It is clear from this and previous research that elite fast bowlers continue to be vulnerable to low back injuries. The following sub-sections consider spinal shrinkage, lumbar curvature, results from musculoskeletal screening and fitness tests, as well as biomechanical technique as risk factors for lower back injury in an elite fast bowling squad.

4.4.2 Spinal shrinkage and curvature

To the author's knowledge, spinal shrinkage and curvature have not been previously measured in a group of elite fast bowlers. After a period of unloading, substantial spinal shrinkage of approximately 5 mm was recorded after bowling five overs. In comparison lumbar curvature was not altered by the acute effects of bowling, thus again supporting the assumption that a loss in stature is predominantly due to alterations to the height of intervertebral discs (IVD) in response to the loading experienced by the spine. The magnitude of height loss supports previous research conducted within amateur bowlers (Reilly & Chana 1994; Barry 2007) and the findings from Studies 1,3 and 5 in this thesis. While the volume of deliveries in this study was lower than in previous research, similarity in the amount of spinal shrinkage could be a result of increased loads on the spine associated with the faster bowling speeds of elite bowlers (Worthington et al., 2013; Middleton et al., 2016).

Injured bowlers experienced significantly more spinal shrinkage than those who were injury free. Despite the small number of injured bowlers, the large effect size indicates that increased shrinkage may be of clinical significance in lower back injuries to elite fast bowlers. An increase in spinal shrinkage implies that the shock absorption properties of the IVDs were reduced, although the clinical importance of the relationship between the amount the spine shrinks, and injury is yet to be established. The loss of IVD height has also been reported to limit the role of the stabilizing muscles, resulting in increased movement of vertebral motion segments (Panjabi 1992). Since the injured bowlers in the current study were diagnosed with spine muscle sprain, tendon strain and lumbar facet joint pain, increased spinal shrinkage may have contributed to a loss in osseoligamentous integrity (Beazell et al., 2010).

Eklund (1988) speculated on the contribution of spinal shrinkage to the aetiology of back injury, through changes on the geometry and physical properties of the spine. Increases in disc bulging, decreased room for the nerve roots, increased tension in the collagen fibres of the annulus fibrosus, increased stiffness of the disc, poor nutritional supply of the disc and increased load on the facet joints were all associated with loss of IVD height. Previous research has also reported that a 1 mm loss in IVD height led to a quadrupling of forces loaded through the facet joints (Adams & Hutton, 1980). With shrinkage volumes for injured bowlers double those of injury free bowlers, more studies into the clinical significance of different amounts and rates of shrinkage in this area are warranted to gain further understanding of how the spine responds to the loads experienced when bowling fast (see Table 4.8).

Due to the retrospective nature of the analysis, it is difficult to ascertain whether the increased shrinkage escalates the risk of injury or that lumbar injury has rendered the IVDs more prone to shrinkage. In support of shrinkage as a risk factor, as described above, previous research has shown that participants with chronic low back pain shrink by similar amounts to those without pain during exercise, but struggle to recover height after unloading, a result of IVD degeneration (Healey et al., 2005). Bowlers in this study increased in stature after unloading, with no difference seen between those who were injured or not injured, indicating that the IVDs of all bowlers were healthy (see Figure 4.5). Moreover, Ranson et al. (2008) reported that bowlers may develop bone problems before disc degeneration and emphasised the need to establish the relationship between acute changes in healthy IVD and lumbar stress injury.

Unloading the spine in the Fowler position for 20 minutes before bowling increased stature by 4 mm, which is more than the 2.6 mm bowlers experienced with five minutes of body inversion reported by Reilly & Chana (1994). With a 1 mm loss in lumbar disc height leading to increased loading through the facet joints, increasing IVD height should help to dissipate forces, particularly early in a bowling spell (Adams & Hutton 1980; Koeller et al., 1984; Bogduk & Twomey 1987;). Applying the findings of this chapter to the game, it might be possible for fast bowlers to unload during the natural breaks in play that occur, such as lunch and tea intervals or between innings to take advantage of the improved shock absorption capacity that this may offer to the IVDs.

Portus et al. (2004) reported that bowlers may flex the front leg at FFC to reduce peak impact forces, thus allowing forces to be dissipated over a longer period, possibly helping to prevent injury. Although no statistical relationship between stature loss and front knee angles during the delivery stride were found, the findings of this chapter show that an extended rear knee that does not collapse during bowling, in combination with an extended front hip at FFC are associated with increased spinal shrinkage. As such bowlers may have less time to dissipate the forces experienced when bowling, and that greater force was transferred to the vertebral column, leading to a greater loss of IVD height. Further research is needed on the size and temporal nature of forces experienced at FFC and BFC in relation to spinal shrinkage.

Thirteen out of 14 bowlers were categorized as having normal lordosis partly due to the classification system having a wide range of 'normal' angles (20-40°) (Been & Kalichman 2014). The lordosis of the injured bowlers was not significantly greater than the non-injured bowlers, however the effect size was large ($r = 0.5$). Whilst small sample sizes, as used in this study, can inflate the effect statistic (Cheung & Slavin 2016) this could be an indication of the importance of increased lordosis as an injury risk factor. Previous research has shown that bowlers with increased lordosis had abnormal radiological features of the lumbar spine (Elliott et al.,1992). More recently, junior bowlers with a previous back injury also possessed a significantly more lordotic curvature than those with no injury history (Hecimovich & Stomski 2016).

Outside sport, research has also highlighted associations between increasing lordosis and lumbar injury (Labelle et al., 2009; Been et al., 2011; Chung et al.,2012). It has been postulated that increased lordosis leads to a greater shear force concentrating on the pars interarticularis (Been et al., 2011). Similarly, research into posture has reported compressive forces transmitted through the facet joints rising from 1% in the neutral position to 16% when lordosis is increased by 2° (Adams & Hutton 1980). This has been attributed to the change in orientation of the inferior articular facet processes, to a more horizontal inclination, as lordosis increases (Been et al., 2014).

Combining an increase in lordotic angle with loss of IVD height, especially in extension, has also been shown to significantly increase forces that could contribute to damage of facet joints (Dunlop et al., 1984). More recently, Rabal-Pelay et al. (2019) showed a significant increase in lumbar lordosis and spinal shrinkage after eight hours standing on a factory production line. The pelvis is considered the base of the spine and its anteroposterior orientation is linked to the lordotic angle of the lumbar region (López- Miñarro et al., 2012). Returning to cricket bowling, Alway et al. (2020) found that anterior pelvic tilt at FFC is a lumbar injury risk factor but they did not consider whether the curvature of the spine influenced tilt. In order to advance our understanding of load and potential injury to the lumbar spine, further research on the morphological responses to bowling over longer time periods, such as a full-day's play maybe warranted. With injured bowlers in this study demonstrating greater spinal shrinkage as well as a more lordotic lumbar curvature, there is a strong argument for including these in screening tests (Been & Kalichman 2014).

4.4.3 Biomechanics of the action

According to the classification of Portus et al. (2004) nine out of 10 bowlers in this study demonstrated a mixed bowling action. Despite early research identifying this action as a lumbar injury risk factor (Burnett et al., 1995; Foster and Elliot, 1989) evidence of this was not found in this sample of elite fast bowlers. More recent research has also found no relationship between the mixed bowling action and lumbar injury (Ranson et al., 2008; Alway et al. 2020;). Increased flexion of the front knee during FFC has been linked to a reduced incidence of lower back injury in fast bowlers (Foster et al., 1989; Portus et al., 2004) but this was not found in the current study. Portus et al. (2004) reported that bowlers who extended their front knee more at BR, experienced higher horizontal and vertical impact forces. One could surmise that such forces may require greater attenuation and thus loss of IVD height, but this was not able to be tested.

Alway et al. (2020) reported that injured bowlers had a more flexed rear knee (146°) and hip (146°) at BFC than non-injured. Front hip angle (130°) at FFC was also significantly more flexed for those who sustained a lumbar injury (Alway et al., 2020). Although the findings in this chapter did not find any statistical differences in biomechanical parameters between injured and non-injured bowlers, mean rear knee and hip angles at BFC (141° and 133°

respectively) and front hip angle at FFC (116°) for all bowlers were lower (i.e., more flexed) than those who suffered a lumbar spine injury in Alway et al's. (2020) research. It is therefore important for the medical staff of the squad of elite bowlers to monitor the bowlers who demonstrated these potential risk factors in future seasons (see Table 4.6).

Lateral spinal flexion at FFC and BR has been implicated in lumbar injury to fast bowlers (Ranson et al., 2008; Ferdinands et al., 2009; Bayne et al 2015), although Alway et al. (2020) reported no difference in contralateral spinal flexion between injured and injury free bowlers. In the current study statistical inference did not support significant differences in lateral spine flexion at BR between the injured and non-injured group. This may, however, have been a result of the limitations of modelling the lumbar spine as a rigid segment, using a vertical line between the mid-points of the shoulders and hips (Crewe et al., 2013). Previous research has divided the measurement of spinal angles into upper and lower trunk when measuring thoraco-lumbar and pelvic-lumbar alterations during the delivery stride, with the latter being associated with an increased injury risk (Ranson et al., 2008; Ferdinands et al., 2009; Bayne et al 2015). A focus on lateral flexion in the lumbo-pelvic region in combination with morphology of this area still requires further investigation.

4.4.4 Fitness tests and musculoskeletal screening

The association between hamstring tightness and IVD abnormalities in fast bowlers has previously been reported by Elliott et al. (1992). Research has hypothesised that lumbar spine pathology (particularly around L5) is a hamstring strain risk factor (Orchard et al., 2010). This may be due to the relationships between degenerative changes in the lumbar spine and the hamstring nerve supply originating from have L5 and S1 (Orchard et al., 2004). However, the bowlers who sustained a lumbar injury in this study demonstrated greater hamstring flexibility in comparison to those who were injury free (see Table 4.7). This may be due to the retrospective nature of the research design and the delay between testing and the occurrence of the lumbar injury in the previous season. Following the injury, hamstring strengthening, and flexibility was part of the rehabilitation process, probably leading to the improved flexibility in this group. Research investigating the lumbar-spine-hamstring injury nexus has also indicated that measurement of hamstring weakness rather than range of motion may be more pertinent as a potential injury risk factor (Orchard et al., 2010).

Statistical analysis did not show significant associations between lumbar injury and all the other fitness and musculoskeletal tests; however, 29% of all bowlers did demonstrate knee valgus on the single leg squat. Previous research reported an association between increased knee valgus during a single leg decline squat and lower back injury (Sims et al., 2010; Bayne et al., 2015). Decreased hip internal rotation and poor ankle dorsiflexion have also been linked to low back injury (Bayne et al., 2015; Olivier et al., 2015).

In the current study the limit of musculoskeletal screening to only once per year, may explain the lack of an association to injury. Screening only once can provide baseline measures on which to calculate a return to play after injury, but the potential lengthy time between assessment and an injury make risk classification difficult (Dennis et al., 2008). The regularity of fitness and musculoskeletal monitoring needs to be researched to enable more insights into the dose-response relationships between playing, training and potential injury. With the increased use of wearable technology such as Global Positioning System units at the elite level, more physical data will become more readily available for continuous analysis (Peterson et al 2009; Johnston et al., 2014; Sholto-Douglas et al., 2020).

4.5 Conclusion

The squad of fourteen elite fast bowlers studied in this PhD experienced significant spinal shrinkage after five overs of bowling, which was higher in those bowlers who sustained a lumbar injury in the 2019 season. Whilst increased lumbar lordosis may be a lumbar injury risk factor, statistical evidence was lacking for an association between biomechanical parameters, fitness levels, musculoskeletal variables and injury. More regular screening throughout the year may be required to monitor potential relationships between lumbo-pelvic stability and injury risk that have been found in previous research. Unloading the spine in the Fowler position for 20 minutes may provide added protection by increasing IVD height, thus improving the spine’s ability to absorb the forces generated when bowling fast. These findings warrant further investigation into the role of curvature and shrinkage as potential injury risk factors when bowling fast.

Chapter 5 – A retrospective analysis of the relationship between workload and injury to fast bowlers.

5.1 Introduction

Measuring workload through the monitoring of distance, intensity and frequency of physical movements required by various sports has been used ubiquitously to assist in the preparation (Chambers et al., 2015) and injury prevention of athletes (Windt et al., 2018). With the addition of 20 over (T20) cricket since 2005, taking around four hours to complete, alongside five-day Test matches, four-day domestic competitions and one-day 50 over matches (Orchard et al., 2015; McNamara et al., 2017), research has monitored the resultant differences to bowling workload (Dennis et al., 2003; Orchard et al., 2009; Hulin et al., 2013; Orchard et al., 2015; Perret et al., 2020; Alway et al. 2020; Tysoe et al., 2020) and physical workload (Peterson et al., 2009; Peterson et al., 2010; Peterson et al., 2011, Vickery et al., 2016) placed on fast bowlers.

Bowling workload has been measured by recording the number of deliveries bowled during a day, a month, season and across match formats (Dennis et al., 2003; Orchard, 2009 et al., 2009; Hulin et al., 2013; Orchard et al., 2015; Perret et al., 2020; Tysoe et al., 2020; Alway et al. 2020), whereas physical workload has been reported in relation to total distance and distances covered at different velocities. Up to 22 km has been recorded in a single day of a multi-day game, 13 km in a one-day format and 5.5 km in a 20 over game (Peterson et al., 2009; Peterson et al., 2010; Peterson et al., 2011, Vickery et al., 2016). These measurements have been categorised as external workload whereas internal workload has used the rate of perceived exertion (RPE) (Feros et al., 2017; Vickery et al., 2017). The product of internal workload and the duration spent performing an activity has been used to estimate the total demands of sporting activities and referred to as session RPE (sRPE) (Haddad et al., 2017).

Professional sport and cricket have increasingly utilised global positioning technology (GPS) devices that include other forms of microtechnology (accelerometers, magnetometers, and gyroscopes) to monitor bowling and physical workload (Peterson et al., 2011, Vickery et al., 2017; Camomilla et al., 2018). Such devices have been shown to be very sensitive at detecting bowling workload during matches and training (McNamara et al., 2015; Jowitt et al., 2020). In addition to bowling workload, intensity of bowling has also been studied utilising the PlayerLoad™ metric obtained from GPS devices (McNamara et al., 2018). Bredt et al. (2020) states that PlayerLoad™ measures the magnitude of changes in acceleration, which will not be exclusive to bowling and may occur during fielding activities. However, the strong association between PlayerLoad™ and different bowling speeds emphasizes that this metric can be used to monitor intensity of bowling (McNamara et al., 2018). Both bowling and physical workloads need to be considered to understand the total demands placed on fast bowlers.

Research has highlighted that both high and low bowling workloads are related to injury (Perret et al., 2020; Alway et al. 2020; Tysoe et al., 2020). Exceeding a weekly total of 234 deliveries has been associated with the risk of sustaining a lumbar stress injury (Away et al., 2019). Similarly, increasing bowling load in both a seven- and forty two-day period by more than two standard deviations (Tyose et al., 2020), and bowling more than 900 deliveries in 90 days have been associated with injury risk (Orchard et al., 2015). Moreover, bowling workload ranging from 84 -188 deliveries per week have been suggested to enhance injury resilience (Dennis et al., 2003; Hulin et al., 2014; Warren et al., 2018), with career bowling workload exceeding 12 000 overs also offering protection (Orchard et al 2015). Similarly, balancing recovery time with maintaining fitness required to bowl is important with less than two (Dennis et al., 2003) and more than five days' rest (Sims et al., 2017) between bowling sessions being associated with an increased injury risk.

Epidemiological research in injury incidence between game formats has reported 194, 271 and 117 injuries per 1000 days of play for T20, 50 over and 4 days formats respectively (Orchard et al., 2016). Alway et al. (2019) highlighted an increased risk of lumbar stress fracture in the English First-class four-day game in mid (July) and late season (September) in English FCCC. Further research in the multi day format has highlighted risk of injury to bowlers delivering more than 50 overs in a single game (Orchard et al., 2009; Orchard et al. 2015). Whilst research exists in relation to bowling workload, to the authors knowledge no research has investigated the relationship between physical workload and injury to fast bowlers.

Aim – To examine the relationship between injury and workload during a first-class cricket season.

Objectives -

Explore the relationship between bowling workload, physical workload, and injury.

Document the bowling and physical workload of fast bowlers across 4-day, 50-over, T20 match formats and training during an English first-class cricket season (2019) using a GPS system.

5.2 Methods

5.2.1 Participants

Ten professional male fast bowlers (mean ± SD age 27.2 ± 5.7 years, height 186.0 ± 7.6 cm and mass 81.1 ± 9.1 kg) provided written informed consent and volunteered to participate in the study. A fast bowler was defined as one where the wicketkeeper was required to stand back from the stumps to receive a delivery (Orchard et al. 2005). The study was granted institutional ethics approval by Manchester Metropolitan University. This observational study spanned the entire 2019 England & Wales county cricket season (1st April – 30th September) with data collected from 46 competitive fixtures (15 x four-day, 13 x 50 over and 18 x T20) and 101 individual bowling training sessions.

5.2.2 Injury surveillance

Permission was given by bowlers and medical staff to analyse retrospective injury surveillance data from the same (2019) season. New and recurrent injuries were classified by the county medical staff according to Orchards' Sports Injury and Illness Classification System (OSIICS) (Orchard et al. 2020). The month and game format when the injury occurred was recorded along with injury type and activity been undertaken.

5.2.3 Bowling workload

Data used to calculate Bowling Workload was obtained by bowlers wearing an Optim Eye S5 GPS units (Catapult, Melbourne, Australia) sampling at 10 Hz, encased in a vest on the upper back. The GPS units were switched on 15 minutes prior to preparing for the game format or training to establish a satellite lock and allow for warm-up bowling activities to be recorded.

The device recorded for the duration of the innings or training session in which bowling took place.

Data used to calculate bowling were downloaded using the Catapult OpenField Software, Version 1.12.0. and exported to a Microsoft Excel spreadsheet. Bowling workload factors were classified as either external (environment related) or internal (person-related) in nature as defined by Olivier et al. (2016). External factors included maximum and average number of deliveries bowled, that were arranged into seasonal, 7-day and 28-day sections to allow comparison of bowlers who sustained an injury during the season with those who had not (Orchard et al., 2015). The specific dates when all three game formats and training sessions were manually recorded to allow further analysis of workloads across formats. The number of days, in conjunction with duration in minutes spent in the game format or in training when bowling occurred allowed weekly, daily, and hourly calculations of workload. The number of deliveries was divided by the minutes spent playing or training and then multiplied by 60 to get the relative number of deliveries per hour. The average days between bowling was obtained by dividing the total number of days not bowled by the number of occasions bowling was not undertaken.

Recent research has demonstrated that the GPS unit displays excellent sensitivity and specificity (>96%) when measuring bowling workload (number of deliveries) in matches and training (Jowitt et al., 2020). The automatic detection of deliveries, for bowling workload, was achieved by an algorithm that utilised data from an inbuilt accelerometer, gyroscope and magnetometer to detect sudden deceleration in conjunction with peaks in the rotation speed of the upper torso particular to the bowling action (McNamara et al., 2015). This microtechnology also allowed the collection of data at 100 Hz, to measure PlayerLoad™, calculated as "the square root of the sum of the squared instantaneous rate of change in acceleration in each of the three vectors (X, Y and Z axis) and divided by 100", represented by arbitrary units (McNamara et al., 2017). PlayerLoad™ was included within bowling workload in this study as its calculation is heavily influenced by the number of deliveries undertaken (McNamara et al., 2015). Relative calculations for PlayerLoad™ were calculated by dividing the metric by total minutes within the game or training format and multiplied by 60 (PlayerLoad per hour). PlayerLoad™ was also divided by deliveries per hour.

Internal bowling workload factors were measured through the collection of RPE, approximately 30 minutes after completion of the bowling using the 10-point Borg scale (Borg, 1998). RPE was multiplied by the total duration of the time spent in the game or training format when bowling took place to obtain sRPE (Fitzpatrick et al. 2018).

5.2.4 Physical workload

The Optim Eye S5 GPS units (Catapult, Melbourne, Australia) sampling at 10 Hz was also used to collect physical workload measures for each match/training session. Total distance covered (m) and distance covered in the following intensity speed bands; low (0-7 km·hr^{-1}), medium (7.1-15 km·hr^{-1}), high (15.1-20 km·hr$^{-1),}$ very-high (20.1-25 km·hr^{-1}), and sprinting (>25 km·hr^{-1}) were analysed using the Catapult OpenField Software, Version 1.12.0. and exported to a Microsoft Excel spreadsheet. The number of high-intensity and sprint efforts were logged if participants spent a minimum of 0.2 seconds at or above a speed of 20.1 km·hr^{-1} and 25 km·hr^{-1}, respectively. All physical workload measures were divided by the number of minutes spent covering the total distance and distances in the speed bands, then multiplied by 60 to calculate the relative measure per hour.

5.2.5 Statistical analysis

The normality of bowling and physical workload data was examined using the Shapiro-Wilk test. Since there was a violation of normality of distribution, a non-parametric Mann-Whitney U test was used to compare all bowling and physical workload variables between the injured and uninjured fast bowlers. Effect sizes were calculated using Cohen's r with 0.1 = small, 0.3 = medium and 0. 5 = large (Coolican, 2009; Firitz et al., 2012). A descriptive analysis of injuries was also undertaken. The fast bowlers were separated into those who sustained an injury in the 2019 season and those who were injury free (Orchard et al., 2015).

A Kruskal-Wallis H test was conducted to compare the effect of game format and training on bowling and physical workloads. For cases of significance a post-hoc pairwise analysis employing Mann-Whitney U tests, adjusted using a Bonferroni correction, was completed with significance set to $p < 0.05$. The assumption of the similarity of distribution of the dependent variable by group was met and thus median values were summarised alongside interquartile ranges (IQR) (Hart 2001).

5.3 Results

Ten fast bowlers amassed a bowling workload total of 20 005 deliveries over the season, with physical workload amounting to a total distance of 3004 km, during 1037 hours of recorded match and training time.

5.3.1 Injury and workload

The 2019 season saw six fast bowlers suffer 12 new injuries, with 50 % occurring during bowling, with all bar one sustained in a 4-day game. Fifty percent of the injuries occurred in mid-season (June-July) with two lumbar injuries (iliolumbar ligament pain and general lumbar pain) recorded, one in July and one in September (see table 5.1).

The maximum number of overs bowled in 28 days was found to be significantly greater for non-injured bowlers (median = 122 overs) compared to the overs bowled immediately prior to injury in injured bowlers (median = 93 overs), with a large effect size ($r = 0.6$) (see Table 5.2). Although no significant differences were found for average duration of the game format or training when bowling occurred, a large effect size ($r = 0.5$) was reported with a median of 172 minutes for non-injured bowlers compared to 158 minutes for those who became injured.

Statistically significantly greater 7-day physical workload distances at velocities of greater than 25 $km \cdot hr^{-1}$ and number of sprints completed were found for non-injured bowlers compared to 7-day values prior to injury for the injured bowlers, with large effect sizes ($r = 0.7$). Season values for these metrics were also greater for the non-injured bowlers but with a small effect size ($r = 0.2$) (see Table 5.4). During a 7-day period the maximum number of high intensity bouts was significantly higher for bowlers not injured compared to the injured bowlers prior to injury. Although the 28-day measures were not significantly different for high intensity bouts, both timeframes showed a large effect size ($r = 0.5$) (see Table 5.4).

Table 5.1 Injury details to First-class county fast bowlers (n=10) during the 2019 season

Month	Injury	Orchard Code	Format	Activity at time of injury
April	none	-	-	-
May	Patella dislocation	KDPX	50 over	Batting
	Head injury	NHCX	4 day	Batting
June	Abdomen pain	OMXX	Training	Fitness work
July	Lumbar muscle pain	LJLI	4 day	Bowling
	Knee contusion	KHXX	4 day	Fielding
	Posterior ankle pain	ACP2	4 day	Bowling
	Ankle sprain	AJLA	Training	Batting
	Abdomen strain	OMRR	4 day	Bowling
August	Calf tightness	OMGM	Training	Fitness work
	Lumbar joint pain	LXXX	4 day	Bowling
September	Ankle contusion	AHXX	4 day	Bowling
	Thigh strain	TMQS	Training	Bowling

5.3.2 Bowling workload

Totalled overs bowled over the season ranged from 329-690 for the elite fast bowlers. Game and training formats had a statistically significant effect on bowling workload (see Tables 5.5). Significantly more deliveries were bowled in 4-day cricket compared to T20 ($p< 0.001$) but Player Load and Player Load per hour/deliveries per hour were significantly higher for the T20 format ($p = 0.002$). This latter metric was also significantly higher in T20 compared to 50 overs ($p = 0.003$) (see Table 5.5). Duration of the innings or training session in which bowling took place and sRPE were significantly lower for T20 compared to 4-day and 50 over formats ($p< 0.001$) (see table 5.5). Training sessions had significantly lower median values ($p< 0.001$) for all bowling workload variables compared to the three game formats, apart from deliveries per hour, where the opposite occurred ($p< 0.001$) (see Table 5.5).

5.3.3 Physical workload

Training and game formats had a significant effect on physical workload including total distance, distances at 7.1-15 km·hr^{-1}, 15.1-20 km·hr^{-1}, > 25 km·hr^{-1} and number of sprints (see Table 5.6). Significantly lower total distance values were found in training compared to the three game formats ($p<0.001$), but these differences were deemed non-significant when calculated per hour. Total distance per hour was significantly higher for T20 compared to 4-day games ($p< 0.001$). Relative distances per hour at lower velocities (7.1-15 km·hr^{-1}, 15.1-20 km·hr^{-1}) were also significantly shorter for 4-day compared to other formats (see Table 5.6). The number of high intensity bouts was significantly higher in 4-day and 50 over games compared to training ($p<0.001$) and T20 matches ($p = 0.002$ and $p = 0.003$ respectively) but again were deemed non-significant when calculated per hour. As players did not reach speeds above 25 km·hr^{-1} in training, significant differences were found for number of sprints completed when compared to the game formats (see Table 5.6).

Table 5.2 Bowling workload (external factors) for injured and non-injured First-class county fast bowlers during the 2019 season.

	Not injured (n = 4)		Injured (n = 8)	
Bowling workload	mdn	IQR	mdn	IQR
Total season overs	444	255	459	277
Average overs per week	20	7	21	3
Average season daily deliveries	42	45	48	42
Total days bowled in season	67	42	62	29
Total days not bowled in a season	91	28	86	52
Average days between bowling	2	1	2	0
Average duration in game/training mins	160	194	137	180
Average deliveries per hour	19	19	21	13
Maximum overs in a week	46	11	58	25
Maximum overs in a month	122	48	139	17
Maximum overs 7 day prior to injury	46	11	34	24
Maximum overs 28 day prior to injury	122*	48	93*	15
Average deliveries 7 day prior to injury	58	43	48	32
Average deliveries 28 day prior to injury	63	28	54	20
Average duration mins 7 day prior to injury	226	151	140	80
Average duration mins 28 day prior to injury	203	99	165	29
PlayerLoad	560	620	529	675
PlayerLoad per hour	241	105	243	86
PL per hour/deliveries per hour	238	103	241	80

* = $p < 0.05$; mdn = median; IQR = interquartile range

Table 5.3 Bowling workload (internal factors) for injured and non-injured First-class county fast bowlers (n=10) during the 2019 season.

	Not injured (n = 4)		Injured (n = 8)	
Bowling workload	mdn	IQR	mdn	IQR
RPE 7 day prior to injury	7	2	5	3
RPE 28 day prior to injury	6	2	5	1
Season RPE	6	3	5	3
Season RPE x duration (sRPE)	895	1431	705	1419

mdn = median; IQR = interquartile range

Table 5.4 Physical workload for injured and non-injured First-class county bowlers across 7, 28 and 183 days.

	Highest 7-day values not injured (n = 4)		7 day values prior to injury (n = 8)		Highest 7-day values not injured (n = 4)		28 day values prior to injury (n = 8)		Season values not injured (n = 4)		Season values injured (n = 8)	
	mdn	IQR	mdn	IQR	mdn	IQR	mdn	IQR	mdn	IQR	mdn	IQR
Total Distance (m)	10887	12198	6960	2917	10147	7002	8695	4207	6699	8825	6952	9030
≤7 km/hr (m)	8011	8074	4549	2257	7002	5244	5695	4078	4922	6124	4504	5869
7.1-15 km/hr (m)	1685	2029	1459	810	1722	661	1797	713	1175	1406	1296	1916
15.1-20 km/hr (m)	527	546	526	234	552	243	653	184	424	370	570	583
20.1-25 km/hr (m)	694	1208	433	251	797	791	360	228	480	733	466	671
>25 km/hr (m)	67*	164	10*	12	73	124	49	62	27	111	6	41
High intentisy Bouts (total)	45	45	37	16	51	31	34	12	35	46	35	133
Number of sprints (total)	2*	3	1*	1	3	3	2	2	1	4	0	2

mdn=median; IQR = interquartile range; * = p < .05

Table 5.5 Bowling workload for First-class county bowlers across three formats of cricket and training during the 2019 season (n=14).

	4 day		50 over		T20		Training		
	median	IQR	median	IQR	median	IQR	median	IQR	x^2
Deliveries (2,3)	72	54.00	60	18.00	36	12.00	36	24.00	75.75
Duration mins (1,4,5)	248	201.00	227	80.00	144	96.00	60	46.00	142.74
Deliveries per hour (1)	19	10.00	18	7.00	15	10.00	34	30.00	75.08
RPE (1)	6	3.00	7	1.00	6	3.00	4	2.00	89.58
RPE x duration (sRPE) (1,4,5)	1524	1806.00	1531	651.00	825	923.00	205	227.00	133.68
PlayerLoad (1)	809	741.00	911	285.00	630	388.00	278	219.00	112.60
PlayerLoad per hour (2,3,5)	223	57.00	241	67.00	272	76.00	296	114.00	60.97
PlayerLoad hr/deliveries hr (2,3,4)	12	5.00	14	4.00	18	11.00	8	4.00	77.39

Pairwise comparisons mean ranks - $p < .001$ - Training v T20, 50 0ver, 4-day = 1; Training v 50 over, 4 day = 2; T20 v 4 day = 3; T20 v 50 over = 4; $p < .05$ - T20 v 4 day = 4; T20 v 50 over = 5

metrics per hour mean ranks $p < .001$ - 4 day v T20, 50 over, Training = 6; Training v T20, 50 over, 4 day = 7; $p < .005$ 4 day v Training, T20 = 8

mdn = median; IQR = interquartile range; sRPE = session rate of perceived exertion; Kruskal Wallis x^2 test statistic for each bowling workload measure (n =3)

Table 5.6 Physical workload for First-class county bowlers across three formats of cricket and training during the 2019 season (n=14).

	4 day				50 over				$m{\cdot}hr^{-1}$	mdn $m{\cdot}hr^{-1}$
	mdn	IQR	mdn $m{\cdot}hr^{-1}$	IQR	mdn	IQR	mdn $m{\cdot}hr^{-1}$	IQR	x^2	x^2
Total Distance (m) $_{(1,8)}$	10013	10045	2919	851	11866	3925	2996	815	110.10	18.36
≤ 7 $km{\cdot}hr^{-1}$ (m) $_{(1)}$	7717	7252	1975	596	7835	2143	2006	538	129.41	6.81
7.1-15 $km{\cdot}hr^{-1}$ (m) $_{(1,6)}$	1627	1731	485	242	2419	1666	600	300	114.41	33.86
15.1-20 $km{\cdot}hr^{-1}$ (m) $_{(1)}$	629	556	19	16	729	402	195	100	52.85	255.52
20.1-25 $km{\cdot}hr^{-1}$ (m) $_{(1,4)}$	714	895	204	181	764	501	196	175	74.68	0.46
>25 $km{\cdot}hr^{-1}$ (m) $_{(1,3,7)}$	28	94	9	26	28	60	8	17	77.68	56.83
Number of High Intensity Bouts (total) $_{(2,3,5)}$	52	59	15	9	55	24	14	9	75.27	2.97
Number of Sprints (total) $_{(1,7)}$	1	4	0	1	2	3	0	1	71.72	55.50
	T20				Training					
	mdn	IQR	mdn $m{\cdot}hr^{-1}$	IQR	mdn	IQR	mdn $m{\cdot}hr^{-1}$	IQR	x^2	x^2
Total Distance (m) $_{(1,8)}$	7949	5355	3380	868	3114	2312	3264	1470	110.10	18.36
≤ 7 $km{\cdot}hr^{-1}$ (m) $_{(1)}$	4727	3771	2142	480	1961	1510	2129	819	129.41	6.81
7.1-15 $km{\cdot}hr^{-1}$ (m) $_{(1,6)}$	1695	1682	707	355	530	396	581	288	114.41	33.86
15.1-20 $km{\cdot}hr^{-1}$ (m) $_{(1)}$	500	352	232	111	322	258	316	238	52.85	255.52
20.1-25 $km{\cdot}hr^{-1}$ (m) $_{(1,4)}$	472	177	192	111	193	369	199	259	74.68	0.46
>25 $km{\cdot}hr^{-1}$ (m) $_{(1,3,7)}$	28	119	11	60	0	2	0	1	77.68	56.83
Number of High Intensity Bouts (total) $_{(2,3,5)}$	30	16	13	6	18	27	15	24	75.27	2.97
Number of Sprints (total) $_{(1,7)}$	1	7	0	3	0	0	0	0	71.72	55.50

Pairwise comparisons mean ranks - $p < .001$ - Training v T20, 50 0ver, 4-day = 1; Training v 50 over, 4 day = 2; T20 v 4 day = 3; $p < .05$ - T20 v 4 day = 4; T20 v 50 over = 5

metrics per hour mean ranks $p < .001$ - 4 day v T20, 50 over, Training = 6; Training v T20, 50 over, 4 day = 7; $p < .005$ 4 day v Training, T20 = 8

mdn = median; IQR = interquartile range; Kruskal Wallis x^2 test statistic for each bowling workload measure (n =3)

5.4 Discussion

This chapter examined the relationship between injury, bowling workload and physical workload during a first-class cricket season. Bowling and physical workload were reported across 4-day, 50-over, T20 match formats and training during the 2019 English first-class cricket season using a GPS system. To the authors knowledge this is the first study, utilising GPS micro technology, to report the bowling workloads of elite fast bowlers across all formats of the game and training over an entire season. Previous research (Peterson et al., 2010) has documented physical workloads, but not with First-class county fast bowlers.

With only two lumbar injuries sustained throughout the season, the analysis of bowling and physical workloads was undertaken for all injuries suffered by bowlers. Of the twelve injuries recorded five occurred during August when three 4-day matches were played in 17 days. Despite this observation no differences in injury status were found between bowlers' season, weekly and daily bowling volume (see Table 5.2). Analysis of bowling workload highlighted that bowlers who were injury free bowled more overs in a 28-day period, spent longer bowling, and experienced a much higher internal load as measured by RPE x deliveries. The weekly delivery total for both injured and non-injured bowlers satisfied the minimum bowling requirement of 84 -188 deliveries per week (Dennis et al., 2003; Hulin et al., 2014; Warren et al., 2018) deemed to increase resilience (see Tables 5.2 and 5.3). The maximum total deliveries bowled in a week by both injured and non-injured bowlers was also within the danger threshold of 234-300 (Alway et al., 2020; Orchard e al., 2009), but was not associated with injury. This study supports previous research where high workloads over periods of 12-26 days are not associated with an increase in injury (Orchard et al., 2015). Both injured and non-injured bowlers reported no statistically significant difference in number of days bowled during the season and their amount of rest between bowling events was in line with previous recommendations for both groups (see Table 5.2) (Dennis et al., 2003). No other statistically significant differences were observed between bowling workload factors and injury, thus lending weight to previous research that found no relationship between injury and spikes in bowling workload (Sims et al., 2017; Bayne et al., 2015).

The seven-day distances covered at high intensity running and sprinting were greater for non-injured bowlers compared to the same period prior to injury for those injured (see

Table 5.4). Similarly, 28-day high intensity running was higher for non-injured bowlers. Recent research from Football has highlighted the protective nature of sprint training in mitigating against lower limb injuries (Malone et al., 2018). As 42% of the injuries to elite fast bowlers reported in this current study were to the lower limb, sprint activities may have offered some protection to the non-injured bowlers. Future research on high intensity running and sprint volumes for fast bowlers may help to enhance advice on injury resilience.

Statistical analysis did not support significant differences between total distance and distances at velocities up to 25 $km \cdot hr^{-1}$ for injured and non-injured bowlers. These findings indicate that fast bowlers' physical workload volumes below high-speed running are not related to injury. As the fast bowlers in this study were elite, their fitness to be able to bowl repeated spells during training and matches should be assumed, thus supporting previous research on the physical requirements of fast bowling (Duffield et al. 2009; McNamara et al., 2013).

The three different game formats (4-day, 50 overs and T20) accounted for 50% of the total days in the season spent bowling, which was less than the 20% reported for international players by Mount et al. (2015 a). This is possibly due to the longer time frame over which the international players were measured, the fact that international matches are longer, and/or the need to protect international bowlers more between matches. Unsurprisingly, more deliveries were bowled in 4-day and 50 over matches when compared to T20 and training as formats dictate the maximum number of overs permissible (4- day no limit, 50 over – 10 over limit and T20 – 4 over limit).

The number of deliveries in a training session (37) was almost identical to the 36 reported for international bowlers by Mount et al. (2015 b) and to the 30 for academy elite bowlers by Vickery et al. (2017), with the latter research conducted during a 12-week pre-season training camp in Australia. The duration spent bowling during training was more than twice that reported by Vickery et al (2017), which might be due to the timing of training (i.e. pre-season v in-season). Training bowling volumes were significantly lower compared to the three different game formats, although when normalised to deliveries per hour the opposite was observed (see Table 5.5). This result is probably a consequence of the time spent wearing the GPS device for data acquisition, with training sessions much shorter duration than bowling during an innings in the different game formats.

The number of deliveries in an innings was higher for 4-day (68) than the 56 reported for Test match bowlers by Mount et al. (2015 b). Similarly, more deliveries were found for 50-over (57 v 49), T20 (36 v 22) and training (37 v 33) in this study compared to their international counterparts by Mount et al. (2015 b). This could be the result of the inclusion of warm-up deliveries to measure total bowling workload (using GPS), whereas Mount et al. (2015b) manually recorded daily activities and did not mention whether warm-up activities had been included.

The period when bowling was recorded in a game format (i.e., during an innings of the opposition) was longer for 4-day matches compared to the T20 format. Interestingly, there was no statistical significant difference in duration when bowling was measured between four-day and 50 over cricket, indicating that the demands of both formats are similar for the fast bowler in a single innings. Thus, with four-day matches generally consisting of two innings, bowling in this format may place similar demands on a bowler to bowling in two 50 over matches separated by a day's rest.

Recording duration spent bowling in isolation does not account for the intensity of the activity, thus expressing this as the number of deliveries per hour allows comparison across formats and indicates bowling intensity (Peterson et al., 2010). There was no difference in deliveries per hour across the three match formats, implying there was no difference in bowling intensity or that comparisons per hour may not be specific enough to measure such differences (see Table 5.5). In the current study fast bowlers wore their GPS devices 15 minutes prior to warm-up for games and the assumption was that all vests were removed as soon as an innings had finished within the game format. This practice may have differed between bowlers and thus future research should time-stamp GPS data to allow separate analysis of warm-ups and match bowling, whilst also recording the time at end of the innings.

Another gauge of the intensity of bowling is the rate of perceived exertion (RPE), which is defined as the conscious sensation of how hard, or strenuous a session of physical work is (Haddad et al., 2017), and was used as an internal measure of bowling workload (Feros et al., 2017). RPE also demonstrated no differences across playing formats, and since no previous research has measured it, comparisons are impossible. The sRPE method has been previously shown to be valid measure of intensity in different activities such as Football

(Impellizzeri et al., 2005) and Australian Football (Scott et al., 2013), as well as for endurance athletes (Foster et al., 2001). When considering match formats, T20 sRPE was lower compared to 4-day and 50 over matches (see Table 5.5). This may seem counterintuitive as the T20 format has been shown to place increased physical demands on players (Peterson et al., 2010). However, as the number of deliveries per hour was the same across formats, reduced total volume of deliveries and the shorter duration of T20 would likely have reduced the fast bowler's sRPE. Training sRPE was higher (308 AU) in this study compared the 124 AU reported by Vickery et al. (2017), which could be related to a greater perception of effort in-season when previous match day workload may add to feelings of fatigue compared to the pre-season results of Vickery et al. (2017).

Further ways to measure the intensity of bowling have included the PlayerLoad™ metric (McNamara et al., 2015). PlayerLoad™ in training was lower than for all the game formats but was more than double the training value of 150 reported by Vickery et al. (2017). T20 PlayerLoad™ was lower than other match formats, but this was reversed for the 4-day comparison when represented per hour (see Table 5.5). The calculation for measuring PlayerLoad™ focusses on changes in acceleration that occur for sudden changes of direction or abrupt initiation or termination of movement (Bredt et al., 2020). Across all formats bowlers may be required to perform such movements when fielding as well as bowling. To try an isolate the PlayerLoad™ when bowling, it was divided by deliveries per hour. This metric was higher for T20 when compared to the two other game formats (see Table 5.5), which is in contrast to differences across formats using both RPE and sRPE, as previously discussed. PlayerLoad™ per hour and PlayerLoad™ /deliveries per hour indicate higher intensity of the T20 format compared to 4-day and are potentially a better indication of the intensity of bowling during T20 matches. With the ability to accurately record the duration of bowling, the number of deliveries and PlayerLoad™ from GPS devices, relative calculations for PlayerLoad™ may allow more detailed analysis of the intensity demands of bowling in the different formats.

Findings from this study support previous research where the majority of fast bowlers' physical workload is performed at low intensity (63 -68% ≤ 7 $km \cdot hr^{-1}$), interspersed with bouts of high intensity running, which mainly reflects the demands of the run-up (Peterson et al., 2010) (see Table 5.7). Although total distances per hour across all formats were lower in the current study compared to previous research, the pattern of lower total distances and distances at lower velocities (7.1-15 km·hr^{-1}, 15.1-20 km·hr^{-1}) for T20 compared to other formats was similar to that of Vickery et al. (2017).

Table 5.7 Physical demands of fast bowling.

		Physical distances in metres per hour (mean ±SD)					
Study	Format	Total Distance	≤ 7 km·hr^{-1}	7-15 km·hr^{-1}	15.1-20 km·hr^{-1}	20.1-25 km·hr^{-1}	> 25 km·hr^{-1}
Current	4 -day	2903 ±809	1982 ±508	486 ±181	22 ±21	215 ±136	22 ±38
Peterson et al 2010	4 -day	3774 ±802	2512 ±258	799 ±173	233 ±89	230 ±133	-
Current	50 over	2761 ±1105	1878 ±612	593 ±266	196 ±82	196 ±113	14 ±18
Peterson et al 2010	50 over	3831 ±839	2520 ±362	785 ±275	220 ±81	316 ±121	-
Vickery et al 2016	50 over	4931 ±788	3733 ±1152	-	1573± 370	-	-
Webster et al 2020	50 over	3640 ±401	2440 ±288	674 ±116	212 ±38	314 ±65	
Current	T20	3343 ±586	2136 ±347	706 ±266	247 ±92	225 ±144	29 ±35
Peterson et al 2009	T20	6367 ±1120	3216 ±663	2065 ±404	544 ±242	542 ±126	
Peterson et al 2010	T20	4171 ±971	2634 ±268	882 ±176	249 ±121	406 ±230	

The number of high intensity bouts was greater in 4-day and 50-overs matches compared to T20 but this difference was not evident when intensity bouts were expressed per hour. This contradicts previous research (see Table 5.6) which observed that as the format becomes shorter, higher relative distances and number of high-intensity efforts are recorded by fast bowlers. This may be due to previous research (Peterson et al., 2010; Vickery et al., 2017) defining a high intensity effort as a speed above 12.6 km·hr^{-1} and a sprint above 18 km·hr^{-1} in comparison to 15.1 and 20.1 km·hr^{-1} used for the same intensities in this study. The setting of thresholds for various speed classifications is determined by the manufacturer of the GPS units. This study and previous research have employed these arbitrary, player-independent speed zone thresholds (see Table 5.6), which ignore the relative physical ability of an individual bowler to reach such speeds. To combat this, individualised (player-dependent) speed zone thresholds based on individual fitness measures have been recommended. Providing individual thresholds will account for the influence of variances in physical fitness and allow a more accurate representation of individual demands of an activity (Hunter et al., 2015). The lack of individualised thresholds is highlighted by the fact that no fast bowlers reported sprints and velocities above 25 km·hr^{-1} in training and this threshold may not have been achievable by some of the bowlers. Individualised thresholds therefore may provide a more valid assessment of physical load and should be conducted in future research (Rago et al., 2020).

Utilising the GPS devices and associated microtechnology in this study, and not simply counting deliveries, has allowed a broader and more complete analysis of the workload of fast bowlers across formats than previous research. For example, in this study use of PlayerLoad™ highlighted the increased demands of T20 cricket. The ability of GPS units to accurately monitor separate deliveries (Jowitt et al., 2020) combined with the physical metrics highlights the future direction of fast bowler workload monitoring. The ability to time-stamp data output and apply individualised thresholds for physical parameters will allow a more forensic analysis of demands placed on fast bowlers within the game format and in training. Such analysis could include recording start of play to separate the demands of the warm-up, duration of spells of bowling, overs bowled in a spell, work to rest ratios and all the associated physical demands that accompany such events. Cricket has introduced a consensus statement on monitoring injury (Orchard et al., 2016) and a similar document is required for workload monitoring to guide future research.

5.5 Conclusion

Analysis of bowling workload across formats showed that more deliveries were bowled in 4-day and 50 over matches when compared to T20, although adjusting for deliveries per hour resulted in no statistically significant difference between formats. Similar bowling and physical workload demands were reported for 4-day compared to 50 over matches. There were contrasting findings regarding intensity of bowling in T20 cricket, with fast bowlers perceiving the demands to be less intense although PlayerLoad™ per hour and PlayerLoad™ /deliveries indicated that the T20 format placed an increased intensity when bowling. Bowling workload in training matches the demands of different match formats providing similar deliveries per hour. Analysis of physical workload showed that a lack of high intensity running and sprinting during bowling training sessions is associated with increased injury rate. Bowling workload was not statistically associated with injury to fast bowlers, therefore, to gain a clearer picture of the total demands placed on a fast bowler both bowling and physical workload must be considered in future research.

Chapter 6 - General discussion, limitations, and future recommendations

6.1 Introduction

The work in this thesis was aimed primarily at investigating whether spinal shrinkage and lumbar curvature should be included in the multifactorial risk assessment associated with injury to elite fast bowlers. The thesis began with a narrative review of a broad spectrum of literature covering the factors associated with injury to fast bowlers, injury modelling and spinal morphology. The second chapter built on the limited research on fast bowling's association with changes to spinal morphology (Reilly & Chana 1994; Barry 2007; Hecimovitch & Stomski 2012). It also examined the reliability of a custom-built laboratory stadiometer and the Spinal Mouse for measuring spinal shrinkage and curvature, respectively. Due to the poor between-day intra-rater reliability of the custom-built stadiometer and the difficulties of using this device in the field, an alternative approach for assessing spinal shrinkage in fast bowlers was sought. Consequently, Chapter 3 examined the reliability and validity of a novel stadiometer incorporating ultrasound technology (Seca 287) to ascertain whether such a device could measure stature changes. The Seca 287 demonstrated good face and concurrent validity, although typical error measurements showed that it would be able to detect only relatively large changes in stature within fast bowlers. As previous research had emphasised the increased demands of elite fast bowling (Vickery et al., 2017), it was hypothesised that elite bowlers have the potential for greater spinal shrinkage which the Seca 287 would be able to measure. Furthermore, as the Spinal Mouse was confirmed as a suitable device for measuring lumbar lordosis, both devices were included in research into the multifactorial nature of injury to elite fast bowlers in the following two chapters.

The incidence and prevalence of lumbar injury for elite fast bowlers during the 2019 English FCCC season were reported in Chapter 4. Furthermore, the relationship between fast bowling, lumbar curvature and spinal shrinkage were examined in conjunction with other injury risk factors (biomechanics of the action, fitness, and musculoskeletal parameters). To complete the measurement of risk factors, Chapter 5 then explored the association between injury, bowling workload and physical workload whilst also documenting the demands of the three game formats (4-day, 50-over and T20) and training over a full season.

This final chapter will review the major findings from the experimental studies documented in the previous chapters, describe some of the limitations of methods used to assess injury risk, and provide recommendations for further research into injury in fast bowlers.

6.2 Review of major findings

6.2.1 Spinal shrinkage

The studies measuring spinal shrinkage (Chapters 2 and 3) showed that between five and eight overs of fast bowling placed a noteworthy load on the spine with shrinkage ranging from 5-6 mm, and similar to the previous findings of, for example Barry, (2007). To the author's knowledge the research presented in this thesis is the first to record spinal shrinkage (~ 5mm) in elite fast bowlers. A plateau in shrinkage around the fourth over may indicate that the shock absorbing capacity of the intervertebral discs is reduced early in a bowling spell, although more research would be needed to assess whether bowling more than five overs would further increase shrinkage in elite bowlers.

Measurement of spinal shrinkage using a custom-built stadiometer proved not to be reliable in the fast bowling environment. Poorer reliability than previously reported for a similar device (e.g. Healey et al., 2005) could be due to the need for participants to repeatedly get in and out of the device, for measurement, combined with difficulty in relaxing after the strenuous activity of bowling. The need for a device that relied less on a participant's skill in repeatedly attaining the appropriate measurement position, in conjunction with ease of experimenter use in a cricket environment, required an alternative device to measure spinal shrinkage.

The Seca 287 stadiometer, which employs ultrasonic sensors to measure height, was trialled as a practical approach to measuring stature loss. Use of experimenter instruction rather than the manufacturer's built-in commands resulted in an acceptable within-day reliability, with ICCs of 1.00 and typical errors of ≤3 mm, supporting recent research (e.g. Elia et al.,2019). The use of ultrasound sensors has been suggested to reduce technical or instrument error (Voss et al., 1990) and may have been linked to the good reliability found. Measurements from the Seca 287 were also reported to be within 1 mm of the value recorded by the 'gold standard' stadiometer. This concurrent validity provided further evidence that the Seca 287 would have the ability to detect statistically significant loss in height in elite bowlers.

Studies within this thesis have reported that unloading of the spine, by placing bowlers in the Fowler position for 20 minutes before bowling, resulted in a stature gain of between 4-5 mm. This growth in stature may be used as an indirect measure of recovery of intervertebral disc height (Healey et al., 2005), potentially improving their shock absorbing properties, and offering added protection to the lower back of fast bowlers. With previous research showing that a 1 mm loss in disc height has quadrupled loading through the facet joints (Adams & Hutton, 1980), the opposite action of increasing disc height may therefore reduce such forces.

6.2.2 Lumbar curvature

The Spinal Mouse had good to high between-day intra-rater reliability measuring sagittal lumbar lordosis in the upright position, allowing lumbar curvature in that plane to be measured within elite players. These results support previous research, which has shown high within-day intra-rater reliability for the same measurement (e.g. Topalidou et al., 2015). To the authors knowledge this is the only study to report sagittal lumbar curvature in elite fast bowlers. The finding that lumbar curvature was not altered by the acute effects of fast bowling supported the assumption that a loss in stature was predominantly due to alterations in the height of intervertebral discs in response to loading during bowling.

6.2.3 Workload

Bowling workload was measured by recording the number of deliveries bowled, expressed relative to the hour, day, month, and season, and compared across the three game formats (4-day, 50-over and T20) as well as training. Physical workload was reported in relation to total distance and distances covered at different velocities. Once again, to the author's knowledge this is the first time that both bowling and physical workload have been reported together over a full season.

More deliveries were bowled in 4-day and 50 over matches than in T20 and training, as formats generally dictate the maximum number of overs permissible. When bowling in four-day and 50 over formats were compared, no differences in the duration of the innings and deliveries per hour were found, highlighting that that the demands of both match formats are similar for the elite fast bowler. Bowling workloads within an innings/session across all formats and training were lower when compared to workloads of international players (Mount et al., 2015 a & b), possibly due to the inclusion of warm -up deliveries.

The calculation of the intensity of bowling as deliveries per hour or RPE revealed no difference across match formats. When measured with session RPE and PlayerLoad, the intensity was found to be lower for bowlers in the T20 format compared 4-day and 50 over formats. However, when PlayerLoad was calculated per hour, and expressed as deliveries per hour, T20 was deemed to be the most intense of the formats for fast bowling. These results indicate that clarity is needed in defining the metrics that most accurately reflect the varying demands of bowling in different formats.

The majority of the First-class elite fast bowlers' physical workload was performed at low speeds (63 -68% ≤ 7 $km \cdot hr^{-1}$). The number of high intensity bouts was greater in 4-day and 50 over games than in T20, although no differences were found when expressed relative to the hour. In contrast, Vickery et al. (2017) reported higher relative distances and number of high-intensity bouts in shorter formats. This may be due to different speed zone classifications (set by the manufacturer in the software) for high intensity running and sprinting (Peterson et al., 2010; Vickery et al., 2017).

6.2.4 Multifactorial analysis of injury to elite fast bowlers

Analysis of an elite fast bowling squad over the 2019 English FCCC season supports previous research demonstrating that elite fast bowlers experience a high injury incidence (e.g. Goggins et al., 2020), with match incidence for bowling per 1000 player days (87.9) and lumbar injuries per 100 player days (77.8) higher than in previous epidemiological research (Orchard et al., 2016). Annual injury prevalence for the whole squad was also higher than in previous research (e.g. Goggins et al., 2020). However, as none of the elite bowlers suffered a lumbar stress fracture in the 2019 season, annual injury prevalence for lumbar spine injury (0.63%) was less than the epidemiological findings either Orchard et al., (2010 [0.83%]) or Goggins et al., (2020 [1.35%]).

The fast bowlers who experienced a lumbar injury were shown to have significantly more spinal shrinkage (8 ±1 mm) than those who were injury free (4 ±3 mm) after five overs of bowling. Despite the small number of injured bowlers, the large effect size indicates that shrinkage during the early overs of a bowling spell may be of clinical significance to lower back injuries in elite fast bowlers. This association between spinal shrinkage and injury may be explained by the loss in osseoligamentous integrity that occurs through the reduction of intervertebral disc height (Beazell et al., 2010). This loss in height has previously been shown to reduce the role of the stabilizing muscles, increasing vertebral motion segment movement, and heightening the risk of injury (Panjabi 1992). Furthermore, greater segmental motion in combination with a loss of disc height could substantially increase facet joint loading (Adams & Hutton, 1980), thus contributing to lower back injury.

Previous research has also highlighted the association between excessive lordosis and lumbar injury (Been et al., 2009). As previously discussed, whilst a large effect size was discovered between lordosis and lumbar injury in this thesis, it needs to be interpreted with caution due to the number of bowlers available in the county squad. Been et al. (2011) reported that a more lordotic posture results in a lumbar facet joint orientation that predisposes the pars interarticularis to a higher shear force (Been et al., 2011). As fast bowlers have been reported to experience large lumbar shear forces during bowling (Crewe et al., 2013), greater lumbar lordosis may further predispose such athletes to lumbar injury.

The biomechanics of the action has been extensively researched in relation to injuries in fast bowlers from Elliott & Foster, (1984) to Alway et al., (2020). All but one of the elite fast bowlers investigated had a mixed action, although, as for the bowlers analysed by Ranson et al. (2008) and Alway et al., (2020), this was not associated with injury. There were also no significant differences in any other biomechanical parameters between injured and non-injured bowlers. However, in Alway et al's. (2020) epidemiological study, the rear knee and hip at back foot contact and the front hip at front foot contact were more extended in the bowlers who suffered a lumbar spine injury. Whilst no significant differences were found between injured and non-injured groups, an extended rear knee, i.e.one that did not collapse during the delivery stride, and an extended front hip just prior to delivery were significantly associated with greater spinal shrinkage. As a possible explanation for these associations, the extended lower limbs may have been less effective in dissipating the ground reaction forces, thus leading to higher compressive forces in the lumbar spine and greater loss of disc height.

No associations were found between lumbar injury and any of the fitness or musculoskeletal tests that the bowlers undertook, apart from hamstring flexibility. Surprisingly, the injured bowlers demonstrated greater hamstring flexibility when compared to those who remained injury free. This can be attributed to the flexibility test taking place after the occurrence of the lumbar injury, i.e. the previous season, and thus the influence of subsequent rehabilitation exercises. Further analysis found that 29% of all bowlers demonstrated knee valgus on the single leg squat test, which has previously been associated with lower back injury (e.g. Bayne et al., 2015), indicating that future monitoring is warranted in squads of fast bowlers.

The external risk factor of bowling workload was not associated with injury, supporting previous research (e.g. Sims et al., 2017). No significant difference was found between injured and non-injured bowlers in the number of days bowled during the season, nor the amount of rest between bowling events. Similarly, high workloads over periods of 12-26 days were not associated with injury risk, in accordance with the findings of Orchard et al. (2015). In the case of physical workload, the total distance and the distances recorded while operating below high-speed running were not related to injury, supporting the assertion that elite bowlers possess the necessary physical requirements to undertake bowling within different game formats. However, there was an association between high intensity running and sprinting, and being injury free. Such high intensity activity has been shown to aid injury prevention in other sports (Buchheit et al., 2020), and with injuries sustained to the lower limb, sprint activities may have offered some protection to the non-injured bowlers.

To advance the study of injury risk analysis in fast bowlers, this thesis has shown that measures of spinal shrinkage and lumbar lordosis should be added to other risk factors that previous research has shown to be associated with injury to fast bowlers. Furthermore, inclusion of these new risk factors should not be viewed in isolation, but as part of an approach that examines the interrelationships between the variables that could potentially lead to injury. To advance such an approach, a new injury model for fast bowlers may aid future research.

6.3 An injury model for cricket

Despite nearly 45 years of research into mechanisms associated with injury to fast bowlers from Davis & Blanksby (1976) to Goggins et al. (2020), this role within cricket continues to report the highest risk of injury incidence and prevalence (Orchard et al., 2016). To date research has taken a predominantly reductionist approach to investigate internal and external risk factors associated with injury (e.g. Olivier et al., 2016). This thesis has provided evidence for spinal shrinkage and lumbar curvature as risk factors, employing a similar reductionist approach. However, in taking such an approach it is difficult to ascertain how the risk factors may interact and how such interactions may contribute to injury.

This limitation can be overcome if there is a paradigm shift in the approach to injury risk analysis in cricket. Although a reductionist approach has allowed researchers to investigate relationships between injury risk factors, future research should focus on the interrelationship of these factors. The interaction of risk factors and how interactions contribute to the development of an injury have been termed a 'complex systems' approach (Hulme & Finch 2015). Inherent in this approach is the non-linearity of the relationship between injury risk factors (Bittencourt et al., 2016). As such, a traditional univariate approach to risk analysis may not suffice, and new methodologies will be required to investigate these relationships. Machine learning may be an appropriate tool to undertake such analysis (Ruddy et al., 2019). This approach comes from the field of computer science and builds algorithms to make predictions regarding injury risk models and profiles (e.g. Decision Trees, Random Forests, Neural Networks) relying on big data to formulate models. As there continues to be a worldwide growth in the use of GPS microtechnology in professional cricket, with the resultant increase in collection of big data on bowling workload and physical workload, machine learning may prove valuable in injury analysis.

The application of a complex systems approach to cricket may reveal that two bowlers respond differently to the same set of risk factors. For example, spinal shrinkage, the number of deliveries bowled in a week, the distances run at high speeds, the performance on a single leg squat test and lateral flexion of the lumbar spine at FFC may all interact in different ways to increase injury risk. Furthermore, these risk factors may interact in different ways for different bowlers, which generate an emerging risk profile that is individual to the bowler and not linked to the risk factors in isolation. The aim for cricket research should be to develop risk profiles and provide personalised injury prevention programmes, giving bowlers with specific characteristics different training advice.

More recently, Edouard & Ford (2020) emphasised that understanding the causation of sporting injuries can be aided by the use of injury aetiology models. Despite the development of general injury models from Meuwisse et al. (2004) to Kalkhoven et al. (2020), only Bayne et al. (2015) has used such a model (Meuwisse et al., 1994) to frame their research into injury in adolescent fast bowlers. In support of this approach, Bertleson et al. (2017) suggested that there is a growing need for individual sports to develop their own models. The reductionist approach is essential, however, in establishing individual associations between risk variables and injury, as the first stage in establishing an injury model for cricket.

Building an injury model for cricket allows the risk factors to be identified for a complex systems approach to injury risk identification. Bittencourt et al. (2016) developed such model for sport injury in general (see Figure 1.8) that formed the basis of the fast-bowling injury aetiology model being proposed in the final part of this thesis (see Figure 6.1). The interconnecting lines in the proposed model indicate possible interactions between injury risk factors for fast bowlers, that Bittencourt et al. (2016) referred to as the complex 'web of determinants' that could interact to raise injury risk.

The links between the risk factors offer numerous possible lines of enquiry to examine different interactions. For example, this thesis highlighted the link between a more extended rear knee at BFC and spinal shrinkage, whilst Alway et al. (2020) showed that an extended rear knee was associated with lumbar injury; highlighting a potential area for further research. Similarly, greater lumbar lordosis (previously linked to increased shear forces on the lumbar facet joints) has been associated with lumbar injury (Hecimovich & Stomski 2016), whilst Crewe et al. (2013) showed that having a more extended front knee, and increased shoulder counter-rotation were related peak shear forces. This model will be altered and developed as more risk factors are discovered and the interrelationships between them are established. The model highlights the basic tenant that injuries occur when the capacity of the fast bowler's internal structures (bone, tendon, ligament or muscle) fails to cope with forces (bowling and other physical workload) being applied (Bayne et al., 2015). In agreement with Nielson et al. (2020) the shifting paradigm towards complexity in injury risk analysis will necessitate that researchers from across the world review methodologies, share data and formulate new research questions. New approaches will involve large sample sizes, and big data will be needed to utilise machine learning in a complex systems approach to injury risk analysis in fast bowlers.

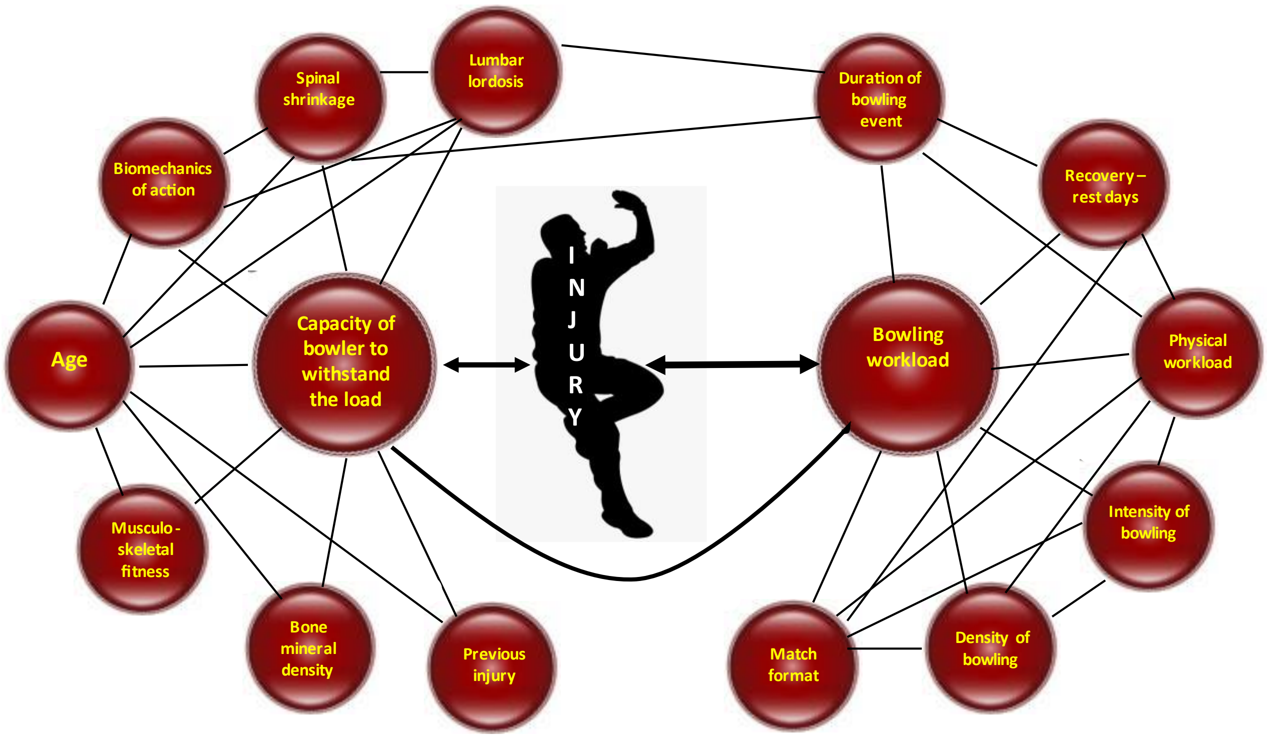
6.4 Limitations

The limitations and the effects that they may have had on the findings were noted throughout the thesis. This section synthesises some of the challenges faced during those studies and the impact they may have had on the research.

The original plan for the studies in Chapters 4 and 5, was to gather data over two seasons and thus undertake both a prospective and retrospective analysis of injuries to fast bowlers. Social distancing due to Covid-19 prevented more data being gathered on the lumbar morphology, fitness, and musculoskeletal measurements during the 2020 season. Unfortunately, the pandemic also resulted in the 2020 English First-class season (August 1st - October 3rd) being severely curtailed and modified, with no 50 over cricket played. This made any in season measurements for 2020 untenable and prevented the comparison of workload variables in game formats across seasons. To address the impact of Covid 19, a more detailed analysis of bowling and physical workload was undertaken for the 2019 season than had originally been planned.

Small sample sizes are a common issue in sport science research, and particularly with elite populations (e.g. Abt et al., 2020), as they imply low statistical power and can lead to a Type II error (i.e. a false negative) (e.g. Rossi, 1990). In response to Abt et al's. (2020) requirement for power calculations to be used for estimating sample size, this was done post-hoc for studies involving the Spinal Mouse and the Seca 287 stadiometer, revealing sample size recommendations of 23 and 33, respectively. However, these numbers were not possible for the studies in Chapters 4 and 5 due to the size of the available First-class elite fast bowling squad that was accessible.

Figure 6.1 Fast-bowling injury aetiology model



Spinal shrinkage – current thesis; **Lumbar lordosis** – Elliot et al., 1992; Hecimovitch & Stomski, 2012; current thesis; **Biomechanics of the action** - Elliott et al., 1992; Elliott et al., 1993; Foster et at., 1989; Elliott & Khangure, 2002; Hardcastle et al., 1992; Portus et al., 2004; Ranson et al., 2008; Crewe et al.,2012; Bayne et al. (2015); Senington et al.,2018; Alway et al., 2020; **Age** - Elliott et al., 1992; Hardcastle et al., 1992; Elliott et al., 1993; Elliott & Khangure, 2002; Burnett et al., 1996; Stretch 2001; Elliott & Khangure, 2002; Crewe et al., 2012; Bayne 2015; Alway et al., 2019. **Musculoskeletal fitness** - Elliott et al., 1992; Cholewicki & VanVliet, 2002; de Visser et al., 2007; Ranson et al., 2008; Sims et al., 2010; Kountouris et al., 2012; Johnson et al., 2012; Olivier et al., 2015; Bayne et al., 2016; **Bone mineral density** - Micklesfield et al., 2012; Lees et al., 2016; Alway et al., 2019; **Bowling workload** - Dennis et al. 2003; Orchard et al., 2009; Hulin et al., 2014; Orchard et al., 2015; Sims et al., 2017; Warren et al., 2018; Alway et al., 2019; Perret et al., 2020; Tysoe et al., 2020; **Recovery-rest days** - Dennis et al., 2003; Sims et al., 2017; **Match format** - Dennis et al., 2003; Orchard et al., 2009; Orchard et al. 2015; Alway et

As the custom-built stadiometer was unreliable in a bowling environment, the Seca 287 was used for fast bowler stature measurements in all subsequent studies. Despite the Seca 287 only having a measurement resolution of 1 mm and not allowing for the head and curvature of the spine to be supported during measuring, it was able to detect loss of stature due to bowling and thus was deemed appropriate to use. The Spinal Mouse was found to produce reliable measures of sagittal lumbar curvature in the upright position. However, poor reliability in this plane for flexed and extended positions in conjunction with poor frontal plane measurements resulted in the omission of these variables from the investigation with elite fast bowlers. It was not possible to measure the validity of this device due to financial constraints, and access to MRI technology. Moreover, ethical considerations would not have allowed asymptomatic participants to be exposed to unnecessary amounts of ionising radiation (i.e. in x-rays). Possibly for these reasons, no studies have measured the validity of the Spinal Mouse for calculating global angles of lordosis or kyphosis in the sagittal plane.

A full 3D biomechanical analysis of elite fast bowlers was conducted, which estimated joint centres by manually digitising video images. This was the most appropriate technique considering the time constraints of working in an elite setting. To have been able to compare the same biomechanical variables, linked to injury, with those presented in recent research (e.g. Alway et al., 2020), a marker based system analysis such as VICON would have needed to be used. Where possible the variables presented in this thesis did match those obtained from such automated systems. However, the lumbar spine was modelled as a rigid segment, using a vertical line between the mid-points of the shoulders and hips. Use of such a simplistic model of the spine may have been the reason that no differences in lateral spine flexion at ball release were found between the injured and non-injured groups. Previous research that divided the trunk into upper and lower segments found, higher lumber lateral flexion to be associated with an increased injury risk (Ranson et al., 2008; Ferdinands et al., 2009; Bayne et al 2015).

To the authors knowledge this was the first study to capture a full season of bowling workload and physical workload together with a full squad of FCCC fast bowlers. Previous research has reported on the excellent intra-device reliability of the Catapult OptimEye S5 units (Nicolella et al., 2018), which allowed large amounts of physical and bowling data to be collected. However, the Catapult units did not allow differentiation between warm-up and match workloads. Physical workload data from the Catapult units utilised speed zone thresholds that were set by the manufacturer, as used in previous research (e.g. Webster et al., 2020). Unfortunately, the Covid-19 pandemic resulted in staff at the England and Wales Cricket Board being furloughed, and it was not possible to access data to individualise the thresholds in relation to the fitness of each individual player.

6.5 Future recommendations

Injured bowlers demonstrated significantly greater spinal shrinkage than those who remained injury free, as well as a large effect size for higher lumbar lordosis. Despite the small sample size used in this thesis, there is a strong argument for including both of these internal risk factors in future investigations into the causes of injury in fast bowlers. Moreover, including these measures in screening tests for fast bowlers will help establish the clinical importance of changes to the spine during fast bowling. To allow this, current commercial stadiometers using ultrasonography (e.g. Seca 287) need to be adapted to improve the measurement resolution closer to the 0.1 mm typical of custom built devices for measuring stature loss. Further research is also required with a larger population of fast bowlers, ideally to reduce typical error to ≤1 mm. This variability was reduced for Seca 287 stature measurements when the experimenter modified instructions were used, therefore manufacturers should consider changing their own inbuilt verbal instructions to reflect these modified instructions.

This thesis has also reinforced that unloading the spine in the Fowler position for 15 to 20 minutes increases stature. It is plausible to suggest that unloading during the natural breaks in play would increase disc height, thereby improving their shock absorbing capacity. Such recommendations may offer some bowlers increased protection to the spine when more than one spell of bowling is required. However, further research is needed to explore the longevity of the acute regain in stature and the most effective unloading protocols.

With stature measurements taking less than one minute, a device such as the Seca 287 stadiometer, with the improvements suggested above, could regularly be used to indirectly monitor the health of fast bowler's discs. Spinal curvature should also be included in a regular screening programme for fast bowlers, especially for those entering and moving through the growth spurt (Hasler 2013). This recommendation supports Ranson et al's

(2007) findings that younger bowlers developed bone problems before disc degeneration. Similarly, previous research has highlighted that younger bowlers (ages 13-18) are at an increased risk of lumbar fracture with the incidence of injury increasing with age through the teen years (e.g. Bayne et al., 2015). Therefore, there is a need to regularly monitor spinal morphology within this population.

Measurement of spinal curvature and spinal shrinkage together would help promote their inclusion as part of a screening programme. A measurement device combining both aspects of spinal morphology assessment would aid the collection of data. For example, an ultrasonographic stadiometer with a built-in contour gauge would allow curvature to be measured alongside stature change. Although more accurate shrinkage measurements have been found for sitting than standing (Pennell et al., 2012), lumbar lordosis is reduced when seated (Cho et al., 2105), therefore a standing device would be preferable. Alternatively, recent research has shown that the microtechnology contained in mobile phones could be used for measuring lumbar curvature (Pourahmadi et al., 2020).

Annual screening of the biomechanics of the action of fast bowlers could be conducted using a similar protocol to that used in the current thesis, as minimal interruption to the training of the elite squad was observed. This may entail a FCCC partnering with, for example, a Higher Education Institution to gain access to the appropriate technology, although an increasing number of clubs are purchasing their own equipment. A focus on rear leg activities during the delivery stride (Alway et al., 2020) and lateral flexion in the lumbo-pelvic region at front foot contact (Bayne et al., 2015) are two areas that have been shown to be linked to injury, and therefore demand further enquiry. Dividing the spine into upper and lower areas for analysis may also aid injury risk analysis (e.g. Bayne et al 2015).

Further research is also needed into which fitness and musculoskeletal measurements are the important injury risk factors and, thus, need to be included in the First-class screening programme. The challenge for the applied practitioner is to integrate meaningful tests into the crowded programme of bowling during matches and training. For example, with the incidence of lower back injury still high, continued focus on the strength of the lumbo-pelvic region for injury prevention may warrant the inclusion of the single-leg squat test.

Furthermore, guidelines on the regularity of such tests within the screening process are needed to aid injury risk analysis.

With the increased use of wearable technology such as Global Positioning System units at the elite level, bowling workload and physical workload data will become more readily available for analysis. To use this data more effectively, investigations into the appropriate use of the PlayerLoad variables to monitor bowling intensity are required. Furthermore, investigations into the number of overs delivered within a spell of bowling, the number of spells, and the rest intervals between spells will allow a more detailed analysis of these as potential injury risk factors for fast bowlers. Guidelines on time-stamping GPS data output and the application of individualised thresholds for physical parameters would also allow differentiation of the demands placed on fast bowlers between warm-ups and match situations.

With the ubiquitous use of GPS units for monitoring bowling and physical workload, the emergence of big data in relation to these variables is inevitable. This will present a challenge to both the practitioner and researcher when dealing with the multitude of metrics from such devices. As such, a new consensus statement on monitoring bowling and physical workload would help future research into the most appropriate metrics, in a similar fashion to the guidance provided by Orchard et al.'s, (2016) statement on bowling injury.

References

Abdel-Aziz, Y.I., and Karara, H.M. (1971). Direct Linear Transformation from Comparator Coordinates into Object Space Coordinates in Close-Range Photogrammetry, *Proceedings of the Symposium on Close-Range Photogrammetry*, 26–29 January, Urbana, Illinois, pp. 1—18.

Abt, G., Boreham, C., Davison, G., Jackson, R., Nevill, A., Wallace, E. and Williams, M. (2020). Power, precision, and sample size estimation in sport and exercise science research. *Journal of Sports Sciences*, 38(17), pp.1933–1935.

Adams, M. and Hutton, W. (1980). The effect of posture on the role of the apophysial joints in resisting intervertebral compressive forces. *The Journal of Bone and Joint Surgery. British volume*, 62-B(3), pp.358–362.

Adams, M.A., Hutton, W.C. and Stott, J. (1980) The resistance to flexion of the lumbar intervertebral joint. Spine, 5(3), pp.245-253

Adams, M.A., Mannion, A. and Dolan, P. (1999) Personal Risk Factors for First-Time Low Back Pain*, Spine*, 24(23), pp.2497.

Adams, M.A., Pollintine, P., Tobias, J.H., Wakley, G.K. and Dolan, P. (2006). Intervertebral Disc Degeneration Can Predispose to Anterior Vertebral Fractures in the Thoracolumbar Spine. *Journal of Bone and Mineral Research*, 21(9), pp.1409–1416.

Alricsson, M. and Werner, S. (2006). Young elite cross-country skiers and low back pain—A 5-year study. *Physical Therapy in Sport*, 7(4), pp.181–184.

Althoff, I., Brinkmann, P., Frobin, W., Sandover, J. and Burton, K. (1992) An improved method of stature measurement for quantitative determination of spinal loading. *Spine,* 17, pp.682-693.

Alway, P., Brooke-Wavell, K., Langley, B., King, M. and Peirce, N. (2019). Incidence and prevalence of lumbar stress fracture in English County Cricket fast bowlers, association with bowling workload and seasonal variation. *BMJ Open Sport & Exercise Medicine*, 5(1), p.e000529.

Alway, P., Felton, P., Brooke-Wavell, K., Peirce, N. and King, M. (2020). Cricket Fast Bowling Technique and Lumbar Bone Stress Injury. *Medicine & Science in Sports & Exercise*, Publish Ahead of Print.

Alway, P., Peirce, N., King, M., Jardine, R. and Brooke-Wavell, K. (2019). Lumbar bone mineral asymmetry in elite cricket fast bowlers. *Bone*, 127, pp.537–543.

Arora, M., Paoloni, J.A., Kandwal, P. and Diwan, A.D. (2014). Are Fast-Bowlers Prone to Back Injuries? Prevalence of Lumbar Spine Injuries in Fast-Bowlers: Review of MRI-Based Studies. *Asian journal of sports medicine*, 5(4), p.e24291.

Atkinson, G. and Nevill, A.M. (1998). Statistical Methods for Assessing Measurement Error (Reliability) in Variables Relevant to Sports Medicine. *Sports Medicine*, 26(4), pp.217–238.

Ayele, B., Aemere, A., Gebre, T., Tadesse, Z., Stoller, N.E., See, C.W., Yu, S.N., Gaynor, B.D., McCulloch, C.E., Porco, T.C., Emerson, P.M., Lietman, T.M. and Keenan, J.D. (2012).

Reliability of Measurements Performed by Community-Drawn Anthropometrists from Rural Ethiopia. *PLoS ONE*, 7(1), p.e30345.

Baharudin, A., Ahmad, M.H., Naidu, B.M., Hamzah, N.R., Zaki, N.O.M., Zainuddin, A.A. and Noor, N.S.M. (2017) Reliability, Technical Error of Measurement and Validity of Height Measurement Using Portable Stadiometer. *Pertanika Journal of Science & Technology* 25(3), pp.675 – 686.

Bahr, R. and Krosshaug, T (2005). Understanding injury mechanisms: a key component of preventing injuries in sport. *British Journal of Sports Medicine*, [online] 39(6), pp.324–329.

Barrett, E., McCreesh, K. and Lewis, J. (2013). Intrarater and Interrater Reliability of the Flexicurve Index, Flexicurve Angle, and Manual Inclinometer for the Measurement of Thoracic Kyphosis. *Rehabilitation Research and Practice*, ID 475870, 7, pp.2013.

Barrett, E., McCreesh, K. and Lewis, J. (2014). Reliability and validity of non-radiographic methods of thoracic kyphosis measurement: A systematic review. *Manual Therapy*, 19(1), pp.10–17.

Barry, T. (2007) 'Spinal shrinkage during eight overs of fast bowling in bowlers with different actions.' *3rd World Congress of Science and Medicine in Cricket.* Barbados Hilton, Barbados, 4-7 April.

Bartlett, R.M., Stockill, N.P., Elliott, B.C. and Burnett, A.F. (1996). The biomechanics of fast bowling in men's cricket: a review. *Journal of Sports Sciences,* 14, pp.403-424.

Bayne, H., Elliott, B., Campbell, A. and Alderson, J. (2016). Lumbar load in adolescent fast bowlers: A prospective injury study. *Journal of Science and Medicine in Sport*, 19(2), pp.117–122.

Beazell, J.R., Mullins, M. and Grindstaff, T.L. (2010) Lumbar instability: an evolving and challenging concept, *Journal of Manual & Manipulative Therapy*, 18(1), pp.9-14.

Been, E. and Kalichman, L. (2014). Lumbar lordosis. *The Spine Journal*, 14(1), pp.87–97.

Been, E., Li, L., Hunter, D.J. and Kalichman, L. (2011) Geometry of the vertebral bodies and the intervertebral discs in lumbar segments adjacent to spondylolysis and spondylolisthesis: pilot study. *European Spine Journal*, 20, pp.1159–65.

Been, E., Pessah, H., Been L., Tawil, A. and Paleg, S. (2007) New method for predicting the lumbar lordosis angle in skeletal material. Anatomical Record, 290, pp.1568–73.

Been. E., Barash, A., Marom, A. and Kramer P.A. (2010) Vertebral bodies or discs: which contributes more to human-like lumbar lordosis? *Clinical Orthopaedics and Related Research*, 468, pp.1822–9.

Berlemann, U., Jeszenszky, D.J., Bühler, D.W. and Harms, J. (1999) The role of lumbar lordosis, vertebral end-plate inclination, disc height, and facet orientation in degenerative spondylolisthesis. *Journal of Spinal Disorders*, 12(1), pp.68-73.

Bertelsen, M.L., Hulme, A., Petersen, J., Brund, R. K., Sørensen, H., Finch, C.F., Partner, E.T. and Nielsen, R.O. (2017) A framework for the etiology of running-related injuries. *Scandinavian Journal of Medicine and Science in Sports*, pp.1–11.

Berthon, P., Fellmann, N., Bedu, M., Beaune, B., Dabonneville, M., Coudert, J. and Chamoux, A. (1997). A 5-min running field test as a measurement of maximal aerobic velocity. European Journal of Applied Physiology, 75(3), pp.233–238.

Beynon, C., Burke, J., Doran, D. and Nevill, A. (2000) Effects of activity-rest schedules on physiological strain and spinal load in hospital-based porters. *Ergonomics*, 43(10), pp.1763-1770.

Bijendra, D., Wu, X., Jiang, Z., Zhu, L., Promish, M. and Ratish, S. (2018). Adjacent Level Vertebral Fractures in Patients Operated with Percutaneous Vertebroplasty. *Open Journal of Orthopedics*, [online] 8(3), pp.116–126.

Bittencourt, N.F.N., Meeuwisse, W.H., Mendonça, L.D., Nettel-Aguirre, A., Ocarino, J.M. and Fonseca, S.T. (2016). Complex systems approach for sports injuries: moving from risk factor identification to injury pattern recognition—narrative review and new concept. *British Journal of Sports Medicine*, 50(21), pp.1309–1314.

Bland, J.M. and Altman, D.G. (1986). Statistical methods for assessing agreement between two methods of clinical measurement. *The Lancet*, 327(8476), pp.307–310.

Bogduk, N. (2005). *Clinical Anatomy of the Lumbar Spine and Sacrum*. Oxford: Elsevier Health Sciences.

Bogduk, N. and Twomey, L.T. (1987). *Clinical anatomy of the lumbar spine*. Melbourne: Churchill Livingstone.

Bolling, C., van Mechelen, W., Pasman, H.R. and Verhagen, E. (2018). Context Matters: Revisiting the First Step of the “Sequence of Prevention” of Sports Injuries. *Sports Medicine*, 48(10), pp.2227–2234.

Boocock, M.G., Garbutt. G., Linge, K., Reilly, T. and Troup J.D. (1990) Changes in stature following drop jumping and post-exercise gravity inversion. *Medicine and Science in Sports and Exercise*, 22(3), pp.385-390.

Boos, N., Wallin, A., Aebi, M. and Boesch, C. (1996) A New Magnetic Resonance Imaging Analysis Method for the Measurement of Disc Height Variations, *Spine,* 21(5), pp.563-570.

Bourne, N.D. and Reilly, T. (1991). Effect of a weightlifting belt on spinal shrinkage. *British Journal of Sports Medicine*, 25(4), pp.209–212.

Bredt, S. da G.T., Chagas, M.H., Peixoto, G.H., Menzel, H.J. and Andrade, A.G.P. de (2020). Understanding Player Load: Meanings and Limitations. *Journal of Human Kinetics*, 71(1), pp.5–9.

Brukner, P., Nealon, A., Morgan, C., Burgess, D. and Dunn, A. (2013). Recurrent hamstring muscle injury: applying the limited evidence in the professional football setting with a seven-point programme. *British Journal of Sports Medicine*, 48(11), pp.929–938.

Bruno, A.G., Burkhart, K., Allaire, B., Anderson, D.E. and Bouxsein, M.L. (2017). Spinal Loading Patterns from Biomechanical Modelling Explain the High Incidence of Vertebral Fractures in the Thoracolumbar Region. *Journal of Bone and Mineral Research*, 32(6), pp.1282–1290.

Buchheit, M., Simpson, B.M., Hader, K. and Lacome, L. (2020) Occurrences of near-to-maximal speed-running bouts in elite soccer: insights for training prescription and injury mitigation, *Science and Medicine in Football*. pp 1-6.

Burnett, A.F., Barrett, C.J., Marshall, R.N., Elliott, B.C. and Day, R.E. (1998). Three-dimensional measurement of lumbar spine kinematics for fast bowlers in cricket. *Clinical Biomechanics*, 13(8), pp.574–583.

Burnett, A.F., Elliott, B.C. and Marshall, R.N. (1995). The effect of a 12-over spell on fast bowling technique in cricket. *Journal of Sports Sciences*, 13(4), pp.329–341.

Burnett, A.F., Khangure, M.S., Elliott, B.C., Foster, D.H., Marshall, R.N. and Hardcastle, P.H. (1996) Thoracolumbar disc degeneration in young fast bowlers in cricket: a follow-up study. Clinical Biomechanics, 11 (6), pp.305-310.

Camomilla, V., Bergamini, E., Fantozzi, S. and Vannozzi, G. (2018). Trends Supporting the In-Field Use of Wearable Inertial Sensors for Sport Performance Evaluation: A Systematic Review. *Sensors*, 18(3), p.873.

Chaise, F.O., Candotti, C.T., Torre, M.L., Furlanetto, T.S., Pelinson, P.P.T. and Loss, J.F. (2011). Validation, repeatability and reproducibility of a noninvasive instrument for measuring thoracic and lumbar curvature of the spine in the sagittal plane. *Brazilian Journal of Physical Therapy*, 15(6), pp.511–517.

Chambers, R., Gabbett, T.J., Cole, M.H. and Beard, A. (2015). The Use of Wearable Microsensors to Quantify Sport-Specific Movements. *Sports Medicine*, 45(7), pp.1065–1081.

Chen, I-Ru. and Wei, T.-S. (2009). Disc Height and Lumbar Index as Independent Predictors of Degenerative Spondylolisthesis in Middle-Aged Women with Low Back Pain. *Spine*, 34(13), pp.1402–1409.

Cheung, A.C.K. and Slavin, R.E. (2016). How Methodological Features Affect Effect Sizes in Education. *Educational Researcher*, 45(5), pp.283–292.

Cho, I.Y., Park, S.Y., Park, J.H., Kim, T.K., Jung, T.W. and Lee, H.M. (2015). The Effect of Standing and Different Sitting Positions on Lumbar Lordosis: Radiographic Study of 30 Healthy Volunteers. *Asian Spine Journal*, 9(5), p.762.

Cholewicki, J. and VanVliet IV, J.J. (2002). Relative contribution of trunk muscles to the stability of the lumbar spine during isometric exertions. *Clinical Biomechanics*, 17(2), pp.99–105.

Chosa, E., Totoribe, K. and, Tajima N. (2004) A biomechanical study of lumbar spondylolysis based on a three-dimensional finite element method. *Journal of Orthopaedic Research*, 22(1), pp.158–63.

Chung, S-B., Lee, S., Kim,H., Lee, S-H., Kim, E.S. and Eoh, W. (2012) Significance of interfacet distance, facet joint orientation, and lumbar lordosis in spondylolysis. *Clinical Anatomy*, 25, pp.391–397.

Coolican, (2009) *Research Methods and Statistics in Psychology*. (5th ed.). Hodder Education Group: London, England.

Corlett, E.N. and Eklund, J.A.E. (1986) Change of stature as an indication of load on the spine. In *The ergonomics of working postures.* London: Taylor Francis. pp.232-242.

Corlett, E.N., Eklund, J.A.E., Reilly, T. and Troup, J.D.G. (1987). Assessment of workload from measurements of stature. *Applied Ergonomics*, 18(1), pp.65–71.

Crewe, H., Campbell, A., Elliott, B.C. and Alderson, J. (2013) Lumbo-pelvic loading during fast bowling in adolescent cricketers: The influence of bowling speed and technique. *Journal of Sports Sciences*, 31(10), pp.1082-1090.

Crewe, H., Elliott, B., Couanis, G., Campbell, A. and Alderson, J. (2012). The lumbar spine of the young cricket fast bowler: An MRI study. *Journal of Science and Medicine in Sport*, 15(3), pp.190–194.

Currier D (1990) *Elements of research in physical therapy* 3 ed., Baltimore: Williams & Wilkins.

Davis, K. and Blanksby, B. (1976) The segmental components of fast bowling in cricket. *Australian Journal of Health and Physical Education Research*, 71(suppl.) pp.6–8.

De Miguel-Etayo, P., Mesana, M.I., Cardon, G., De Bourdeaudhuij, I., Góźdź, M., Socha, P., Lateva, M., Iotova, V., Koletzko, B.V., Duvinage, K., Androutsos, O., Manios, Y. and Moreno, L.A. (2014). Reliability of anthropometric measurements in European preschool children: the ToyBox-study. *Obesity Reviews*, 15, pp.67–73.

De Puky, P. (1935) The physiological oscillation of the length of the body. *Acta Orthopaedica Scandinavia*, 6, pp.338-347.

de Visser, H., Adam, C.J., Crozier, S. and Pearcy, M.J. (2007). The role of quadratus lumborum asymmetry in the occurrence of lesions in the lumbar vertebrae of cricket fast bowlers. *Medical Engineering & Physics*, 29(8), pp.877–885.

Dennis, R., Farhart, R., Goumas, C. and Orchard, J. (2003). Bowling workload and the risk of injury in elite cricket fast bowlers. *Journal of Science and Medicine in Sport*, 6(3), pp.359–367.

Dennis, R.J., Finch, C.F., McIntosh, A.S. and Elliott, B.C. (2008). Use of field-based tests to identify risk factors for injury to fast bowlers in cricket. *British Journal of Sports Medicine*, 42(6), pp.477–482.

Dowzer, C.N., Reilly, T. and Cable, N.T. (1998). Effects of deep and shallow water running on spinal shrinkage. *British Journal of Sports Medicine*, 32(1), pp.44–48.

Duffield, R., Carney, M. and Karppinen, S. (2009) Physiological responses and bowling performance during repeated spells of medium-fast bowling. *Journal of Sports Sciences*, 27(1), pp.27-35.

Dunlop, R., Adams, M. and Hutton, W. (1984). Disc space narrowing and the lumbar facet joints. *The Journal of Bone and Joint Surgery. British volume*, 66-B(5), pp.706–710.

Edouard, P. and Ford, K.R. (2020). Great Challenges Toward Sports Injury Prevention and Rehabilitation. *Frontiers in Sports and Active Living*, 2(80).

Eklund, (1988) Body height changes as a measure of spinal loads and properties of the spine in *Ergonomics in rehabilitation.* Edited by Mital, A and Karwowski, V. Taylor and Francis: London.

Eklund, J.A.E. and Corlett, E.N. (1987) Shrinkage as a measure of load on the spine. *Spine*, 9, pp.189-194.

Elia, M., Cawood, A.L., Akbar, T. and Smith, T. (2019). Nutritional self-screening in. *Nutrition*, 67-68, p.110529.

Elliott, B. and Khangure, M. (2002). Disk degeneration and fast bowling in cricket: an intervention study. *Medicine & Science in Sports & Exercise*, 34(11), pp.1714–1718.

Elliott, B.C. and Anderson, J. (2007) Laboratory versus field testing in cricket bowling: A review of current and past practice in modelling techniques. *Sports Biomechanics*, 6(1), pp. 99-108.

Elliott, B.C. and Foster, D.H. (1984). A biomechanical analysis of the front-on and side-on fast bowling techniques. *Journal of Human Movement Studies*, 10, pp.83-94.

Elliott, B.C., Davis, J.W., Khangure, M.S., Hardcastle, P. and Foster, D. (1993). Disc degeneration and the young fast bowler in cricket. *Clinical Biomechanics*, 8(5), pp.227–234.

Elliott, B.C., Foster, D.H. and Gray, S. (1986). Biomechanical and physical factors influencing fast bowling. *Australian Journal of Science and Medicine in Sport*, 18, pp.16-21.

Elliott, B.C., Foster, D.H. and John, D. (1990). The biomechanics of side-on and front-on fast bowling in cricket. *Sports Coach*, 13, pp.8-11.

Elliott, B.C., Hardcastle, P.H., Burnett, A.E. and Foster, D.H. (1992). The influence of fast bowling and physical factors on radiologic features in high performance young fast bowlers. *Sports Medicine, Training and Rehabilitation*, 3(2), pp.113–130.

Engstrom, C.M. and Walker, D.G. (2007) Pars interarticularis stress lesions in the lumbar spine of cricket fast bowlers. *Europe PMC*. [online] Europepmc.org. Available at: https://europepmc.org/article/med/17218880.

Ferdinands, R.E.D., Kersting, U. and Marshall, R.N. (2009). Three-dimensional lumbar segment kinetics of fast bowling in cricket. *Journal of Biomechanics*, 42(11), pp.1616–1621.

Feros, S., Young, W. and O'Brien, B. (2017). Real-time prediction of internal load during cricket fast bowling. *Journal of Science and Medicine in Sport*, 20, p.53.

Finch, C. (2006). A new framework for research leading to sports injury prevention. *Journal of Science and Medicine in Sport*, 9(1-2), pp.3–9

Foden, M., Astley, S., Comfort, P., J. McMahon, J., J. Matthews, M. and A. Jones, P. (2015). Relationships between speed, change of direction and jump performance with cricket specific speed tests in male academy cricketers. *Journal of Trainology*, 4(2), pp.37–42.

Fölsch, C, Schlögel, S., Lakemeier, S., Wolf, U., Timmesfeld, N. and Skwara, A. (2012) Test-Retest Reliability of 3D Ultrasound Measurements of the Thoracic Spine. *American Academy of Physical Medicine and Rehabilitation,* 4, pp.335-341.

Förster, R., Penka, G., Bösl, T. and Schöffl, V. (2008). Climber's Back – Form and Mobility of the Thoracolumbar Spine Leading to Postural Adaptations in Male High Ability Rock Climbers. *International Journal of Sports Medicine*, 30(01), pp.53–59.

Foster, C., Florhaug, J., Franklin, J., Gottschall, L., Hrovatin, L.A., Parker, S., Doleshal, P. and Dodge, C. (2001) A New Approach to Monitoring Exercise Training. *Journal of Strength and Conditioning Research*, 15(1), pp.109-115.

Foster, D., John, D., Elliott B., Ackland, T. and Fitch K. (1989) Back injuries to fast bowlers in cricket: a prospective study. *British Journal of Sports Medicine*, 23(3), pp.150–154.

Foster, D., John, D., Elliott, B., Ackland T. and Fitch K. (1989) Back injuries to fast bowlers in cricket: a prospective study. *British Journal of Sports Medicine*, 23(3), pp.150–4.

Fowler, N.E., Lees, A. and Reilly, T. (1997) Changes in stature following plyometric drop-jump and pendulum exercises, *Ergonomics*, 40(12), pp.1279-1286.

Fredrickson, B.E., Baker, D., McHolick, W.J, Yan, H.A and Lubicky, J.P (1984) The Natural History of Spondylolysis and Spondylolisthesis. Journal of Joint Bone Surgery, 66(5), pp.699-707

Fritz, C.O., Morris, P.E. and Richler, J.J. (2012). Effect size estimates: Current use, calculations, and interpretation. *Journal of Experimental Psychology: General,* 141(1), pp.2-18.

Frost, W.L. and Chalmers, D.J. (2012). Injury in elite New Zealand cricketers 2002–2008: descriptive epidemiology. *British Journal of Sports Medicine*, 48(12), pp.1002–1007.

Garbutt, G., Boocock, M.G., Reilly, T. and Troup J.D. (1990) Running speed and spinal shrinkage in runners with and without low back pain. *Medicine and Science in Sports and Exercise*, 22(6), pp.769-772.

Garbutt, G., Boocock, M.G., Reilly, T. and Troup, J.D.G. (1994) Physiological and spinal responses to circuit weight-training. *Ergonomics*. 37, pp.117-125.

Geeta, A., Jamaiyah, H., Safiza, M. N., Khor, G. L., Kee, C. C., Ahmad, A. Z. and Faudzi, A. (2009). Reliability, technical error of measurements and validity of instruments for nutritional status assessment of adults in Malaysia. *Singapore Medical Journal*, 50(10), pp.1013.

Glazier, P.S. and Wheat, J.S. (2013). An Integrated Approach to the Biomechanics and Motor Control of Cricket Fast Bowling Techniques. *Sports Medicine*, 44(1), pp.25–36.

Goggins, L., Peirce, N., Ranson, C., McCaig, S., Newman, D., Langley, B., Griffin, S., Young, M., McKay, C., Stokes, K. and Williams, S. (2020). Injuries in England and Wales elite men's domestic cricket: A nine season review from 2010 to 2018. *Journal of Science and Medicine in Sport,* pp1-5.

Gómez-Cabello, A., Vicente-Rodríguez, G., Albers, U., Mata, E., Rodriguez-Marroyo, J.A., Olivares, P.R., Gusi, N., Villa, G., Aznar, S., Gonzalez-Gross, M., Casajús, J.A. and Ara, I. (2012). Harmonization Process and Reliability Assessment of Anthropometric Measurements in the Elderly EXERNET Multi-Centre Study. *PLoS ONE*, 7(7), p.e41752.

Goode, J.D and Theodore, B.M. (1983) Voluntary and Diurnal Variation in Height and Associated Surface Contour Changes in Spinal Curves. *Engineering in Medicine*, 12(2), pp.99-101.

Gower, W.E. and Pedrini, V. (1969) Age-Related Variations in Proteinpolysaccharides from Human Nucleus Pulposus, Annulus Fibrosus, and Costal Cartilage, *The Journal of Joint & Bone Surgery*, 51(6), pp.1154-1162.

Grabara, M. (2012) Analysis of body posture between young football players and their untrained peers (2012), Human Movement, 13(2), pp.120-126.

Gravina, A.R., Ferraro, C., Feizziero, A., and Masiero, S. (2012) Goniometer evaluation of thoracic kyphosis and lumbar lordosis in subjects during growth age: a validity study. *Studies in Health Technology Information*, 176, pp.247-251.

Haddad, M., Stylianides, G., Djaoui, L., Dellal, A. and Chamari, K. (2017) Session-RPE Method for Training Load Monitoring: Validity, Ecological Usefulness, and Influencing Factors. *Frontiers in Neuroscience*, 11(612), pp.1-14.

Hardcastle, P.H., Annear, P.T., Foster, D.H., Chakera, T.M., McCormick, C., Khangure, M. and Burnett, A.F. (1992). Spinal abnormalities in young fast bowlers. *Journal of Bone and Joint Surgery*, 74B, pp.421-425.

Harris, p. and Ranson, C. (2011). *The Back: Anatomy for Problem Solving in Sports Medicine.* Nottingham University Press.

Harrison, D.E., Harrison, D.D., Cailliet, R., Janik, T.J. and Holland, B. (2001) Radiographic Analysis of Lumbar Lordosis Centroid, Cobb, TRALL, and Harrison Posterior Tangent Methods, *Spine*, 26(11), pp.e235-e242.

Hart, A. (2001) Mann-Whitney test is not just a test of medians: differences in spread can be important. *British Medical Journal*, 323(7309) pp.391.

Healey, E.L., Burden, A.M., McEwan, I. and Fowler, N.E. (2008). Stature loss and recovery following a period of loading: Effect of time of day and presence or absence of low back pain. *Clinical Biomechanics*, 23(6), pp.721-726.

Healey, E.L., Fowler, N.E., Burden, A.M. and McEwan, I.M. (2005). The influence of different unloading positions upon stature recovery and paraspinal muscle activity. *Clinical Biomechanics*, 20(4), pp.365–371.

Hecimovich, M.D. and Stomski, N.J. (2016). Lumbar Sagittal Plane Spinal Curvature and Junior-Level Cricket Players. *International Journal of Athletic Therapy and Training*, 21(2), pp.47–52.

Hewett, T.E. and Bates, N.A. (2018) Preventive Biomechanics: A Paradigm Shift With a Translational Approach to Injury Prevention. The American Journal of Sports Medicine, 45(11), pp.2654 – 2664.

Heyward, V.H. and Wagner, D.R. (1994) *Applied Body Composition Assessment*. Human Kinetics: Leeds, UK.

Hopkins, W.G. (2000). Measures of Reliability in Sports Medicine and Science. *Sports Medicine*, 30(1), pp.1–15.

Hulin, B.T., Gabbett, T.J., Blanch, P., Chapman, P., Bailey, D. and Orchard, J.W. (2013). Spikes in acute workload are associated with increased injury risk in elite cricket fast bowlers. *British Journal of Sports Medicine*, 48(8), pp.708–712.

Hulin, B.T., Gabbett, T.J., Blanch, P., Chapman, P., Bailey, D. and Orchard, J.W. (2013). Spikes in acute workload are associated with increased injury risk in elite cricket fast bowlers. *British Journal of Sports Medicine*, [online] 48(8), pp.708–712.

Hulme, A. and Finch, C.F. (2015). From monocausality to systems thinking: a complementary and alternative conceptual approach for better understanding the development and prevention of sports injury. *Injury Epidemiology*, 2(1), pp1-12.

Hunter, F., Bray, J., Towlson, C., Smith, M., Barrett, S., Madden, J., Abt, G. and Lovell, R. (2014). Individualisation of Time-Motion Analysis: A Method Comparison and Case Report Series. *International Journal of Sports Medicine*, 36(01), pp.41–48.

Hwang, J.-H., Modi, H.N., Suh, S.-W., Hong, J.-Y., Park, Y.-H., Park, J.-H. and Yang, J.-H. (2010). Reliability of Lumbar Lordosis Measurement in Patients with Spondylolisthesis. *Spine*,35(18), pp.1691–1700.

Impellizzeri, F.M., Rampinini, E. and Marcora, S.M. (2005) Physiological assessment of aerobic training in soccer. *Journal of Sports Sciences*, 23(6), pp.583-592.

Impellizzeri, F.M., Tenan, M.S., Kempton, T., Novak, A. and Coutts, A.J. (2020). Acute:Chronic Workload Ratio: Conceptual Issues and Fundamental Pitfalls. *International Journal of Sports Physiology and Performance*, 15(6), pp.907–913.

Jackson, R.P. and McManus, A.C. (1994) Radiographic analysis of sagittal plane alignment and balance in standing volunteers and patients with low back pain matched for age, sex, and size. A prospective controlled clinical study. *Spine*, 19(14), pp.1611-1618.

Johnson, M., Ferreira, M. and Hush, J. (2012). Lumbar vertebral stress injuries in fast bowlers: a review of prevalence and risk factors. *Physical Therapy in Sport*, 13(1), pp.45–52.

Johnston, R.J., Watsford, M.L., Kelly, S.J., Pine, M.J. and Spurrs, R.W. (2014). Validity and Interunit Reliability of 10 Hz and 15 Hz GPS Units for Assessing Athlete Movement Demands. *Journal of Strength and Conditioning Research*, 28(6), pp.1649–1655.

Jowitt, H.K., Durussel, J., Brandon, R. and King, M. (2020) Auto detecting deliveries in elite cricket fast bowlers using microsensors and machine learning, *Journal of Sports Sciences*, 38(7), pp.767-772.

Kalichman, L., Li L., Hunter, D.J. and Been, E. (2011) Association between computed tomography-evaluated lumbar lordosis and features of spinal degeneration, evaluated in supine position. *Spine Journal*, 11(4), pp.308–315.

Kalkhoven, J.T., Watsford, M.L. and Impellizzeri, F.M. (2020). A conceptual model and detailed framework for stress-related, strain-related, and overuse athletic injury. *Journal of Science and Medicine in Sport*.

Kanlayanaphotporn, R., Williams, m., Fulton, I. and Trott, P. (2002) Reliability of the vertical spinal creep response measured in sitting (asymptomatic and low-back pain subjects). *Ergonomics*, 45(3), pp.240-247.

Kapitán,M., Pilbauerová, N., Vavřičková, L., Šustová, Z. and Machač, S. (2019) Prevalence of Musculoskeletal Disorders Symptoms among Czech Dental Students. Part 2: the Predictive Value of Digital Assessment. *Acta Medica*, 62(1),pp.6–11.

Keller, S., Mannion, A. and Grob, D. (2000) Reliability of new measuring device Spinal Mouse in recording saggital profile of the back. *European Spine Journal*, 9(4), pp.282.

Kellis, E., Adamou, G., Tzilios, G. and Emmanouilidou, M. (2008). Reliability of Spinal Range of Motion in Healthy Boys Using a Skin-Surface Device. *Journal of Manipulative and Physiological Therapeutics*, 31(8), pp.570–576.

Kimura, S., Steinbach, G., Watenpaugh, D.E. and Hargens, A.R. (2001) Lumbar Spine Disc Height and Curvature Responses to an Axial Load Generated by a Compression Device Compatible with Magnetic Resonance Imaging, *Spine*, 26(23), pp.2596-2600.

Koeller, W., Meier, W. and Hartmann, F. (1984) Biomechanical properties of human intervertebral discs subjected to axial dynamic compression. A comparison of lumbar and thoracic discs. *Spine*, 9(7), pp.725-733.

Kountouris, A., Portus, M. and Cook, J. (2012). Quadratus lumborum asymmetry and lumbar spine injury in cricket fast bowlers. *Journal of science and medicine in sport*, 15(5), pp.393–7.

Kraemer, J., Kolditz, D. and Gowin, R. (1985) Water and electrolyte content of human intervertebral discs under variable load. *Spine*, 10(1), pp.69-71.

Kuiper, J.I., van Dieën, J.H., Everts, V., Verbeek, J.H.A.M. and Frings-Dresen, M.H.W. (2004). Associations between serum markers of collagen metabolism and spinal shrinkage. *Clinical Biomechanics*, 19(2), pp.209–212.

Labelle, H., Roussouly, P., Berthonnaud, E., Mac-Thiong, J.M., Hresko, M.T., Dimar, J.R., Parent, S., Weidenbaum, M., Brown, C. and Hu, S.S. (2009) Spondylolisthesis Classification Based on Spino-Pelvic Alignment: Paper #46, *Spine Journal Meeting Abstracts,* 10, pp.85–86.

Langley,B., Ranson, C. and Moore, I. (2015) Five-year epidemiology of muscle injuries in professional cricket. *5th World Congress of Science and Medicine in Cricket 2015*: Luna Park, Sydney, 23-27 March.

Leary, T. and White, J.A. (2000). Acute injury incidence in professional county club cricket players (1985-1995). *British Journal of Sports Medicine*, 34(2), pp.145–147.

Leatt, P., Reilly, T. and Troup, J.G. (1986). Spinal loading during circuit weight-training and running. *British Journal of Sports Medicine*, 20(3), pp.119–124.

Lees, M.J., Bansil, K. and Hind, K. (2016) Total, regional and unilateral body composition of professional English first-class cricket fast bowlers. *Journal of Sports Sciences*, 34(3), pp.252-258.

Leivseth, G., and Drerup, B. (1997) Spinal Shrinkage During Work in a Sitting Posture Compared to Work in a Standing Posture. *Clinical Biomechanics*, 12(7–8), pp.409–418.

Lewis, S.E. and Fowler, N.E. (2009). Changes in Intervertebral Disk Dimensions After a Loading Task and the Relationship With Stature Change Measurements. *Archives of Physical Medicine and Rehabilitation*, 90(10), pp.1795–1799.

Livanelioglu, A., Kaya, F., Nabiyev, V., Demirkiran, G., Tüzün F. (2015) The validity and reliability of ''Spinal Mouse'' assessment of spinal curvatures in the frontal plane in pediatric adolescent idiopathic thoraco-lumbar curves. *European Spine Journal*, 25, pp. 476-482.

Lockie, R.G., Murphy, A.J., Schultz, A.B., Jeffriess, M.D. and Callaghan, S.J. (2013). Influence of Sprint Acceleration Stance Kinetics on Velocity and Step Kinematics in Field Sport Athletes. *Journal of Strength and Conditioning Research*, 27(9), pp.2494–2503.

Lombard, W.P. and Muir, G.A. (2012). Minimal changes in indirect markers of muscle damage after an acute bout of indoor pre-season fast bowling. *South African Journal for Research in Sport, Physical Education and Recreation*, 34(2), pp.105–114.

Lopez-Miñarro, P. A., Maria Muyor, J., Alacid, F., Vaquero-Cristobal, R., Lopez-Plaza, D., & Isorna, M. (2013). Comparison of hamstring extensibility and spinal posture between kayakers and canoeists. *Kinesiology*, 45(2), 163–170.

López-Miñarro, P.A. and Alacid, F. (2010). Influence of hamstring muscle extensibility on spinal curvatures in young athletes. *Science & Sports*, 25(4), pp.188–193.

López-Miñarro, P.A. and Muyor, J.M. (2017). Comparison of sagittal spinal curvatures and pelvic tilt in highly trained athletes from different sport disciplines. *Kinesiology*, 49(1), pp.109–116.

López-Miñarro, P.A., Muyor, J.M. and Alacid, F (2012) Influence of hamstring extensibility on sagittal spinal curvatures and pelvic tilt in highly trained young kayakers, *European Journal of Sport Science*, 12(6), pp.469-474.

Lord, M.J., Small, J.M., Dinsay, J.M. and Watkins, R.G. (1997) Lordosis: Effects of Sitting and Standing, *Spine*, 22(21), pp.2571-2574.

MacLean, J.J., Owen, J.P. and Iatridis, J.C. (2007). Role of endplates in contributing to compression behaviors of motion segments and intervertebral discs. *Journal of Biomechanics*, 40(1), pp.55–63.

Mac-Thiong, J.-M., Labelle, H., Charlebois, M., Huot, M.-P. and de Guise, J.A. (2003). Sagittal Plane Analysis of the Spine and Pelvis in Adolescent Idiopathic Scoliosis According to the Coronal Curve Type. *Spine*, 28(13), pp.1404–1409.

Magnusson, M., Hansson, T. and Pope, M.H. (1994). The effect of seat back inclination on spine height changes. *Applied Ergonomics*, 25(5), pp.294–298.

Magnusson, M.L., Aleksiev, A.R., Spratt, K.F., Lakes, R.S. and Pope, M.H. (1996) Hyperextension and Spine Height Changes. *Spine*, 21(22), pp.2670-2675.

Malone, S., Owen, A., Mendes, B., Hughes, B., Collins, K. and Gabbett, T.J. (2018). High-speed running and sprinting as an injury risk factor in soccer: Can well-developed physical qualities reduce the risk? *Journal of Science and Medicine in Sport*, 21(3), pp.257–262.

Mannion, A.F., Knecht, K., Balaban, G., Dvorak, J. and Grob, D. (2004). A new skin-surface device for measuring the curvature and global and segmental ranges of motion of the spine: reliability of measurements and comparison with data reviewed from the literature. *European Spine Journal*, 13(2), pp.122–136.

Maunder, E., Kilding, A.E. and Cairns, S.P. (2017). Do Fast Bowlers Fatigue in Cricket? A Paradox Between Player Anecdotes and Quantitative Evidence. *International Journal of Sports Physiology and Performance*, 12(6), pp.719–727.

McGill, S. (2015). *Low Back Disorders: Evidence-Based Prevention and Rehabilitation*. Champaign, Illinois: Human Kinetics.

McGill, S.M., Van Wijk, M.J., Axler, C.T. and Gletsu, M. (1996). Studies of spinal shrinkage to evaluate low-back loading in the workplace. *Ergonomics*, 39(1), pp.92–102.

McIntosh, A.S. (2005). Risk compensation, motivation, injuries, and biomechanics in competitive sport. *British Journal of Sports Medicine*, 39(1), pp.2–3.

McNamara, D.J., Gabbett, T.J. and Naughton, G. (2017). Assessment of Workload and its Effects on Performance and Injury in Elite Cricket Fast Bowlers. *Sports Medicine*, 47(3), pp.503–515.

McNamara, D.J., Gabbett, T.J., Blanch, P. and Kelly, L. (2018). The Relationship Between Variables in Wearable Microtechnology Devices and Cricket Fast-Bowling Intensity. *International Journal of Sports Physiology and Performance*, 13(2), pp.135–139.

McNamara, D.J., Gabbett, T.J., Chapman, P., Naughton, G. and Farhart, P. (2015). The Validity of Microsensors to Automatically Detect Bowling Events and Counts in Cricket Fast Bowlers. *International Journal of Sports Physiology and Performance*, 10(1), pp.71–75.

McNamara, D.J., Gabbett, T.J., Naughton, G., Farhart, P. and Chapman, P. (2013). Training and Competition Workloads and Fatigue Responses of Elite Junior Cricket Players. *International Journal of Sports Physiology and Performance*, 8(5), pp.517–526.

Meeuwisse, W.H. (1994) Assessing Causation in Sport Injury: A Multifactorial Model. *Clinical Journal of Sport Medicine*, 4(3), pp.166-170

Meeuwisse, W.H., Tyreman, H., Hagel, B. and Emery, C. (2007). A Dynamic Model of Etiology in Sport Injury: The Recursive Nature of Risk and Causation. *Clinical Journal of Sport Medicine*, 17(3), pp.215–219.

Micklesfield, L.K., Gray, J. and Taliep, M.S. (2012) Bone mineral density and body composition of South African cricketers. *Journal of Bone Mineral Metabolism*, 30, pp.232–237

Middleditch, A. and Oliver, J. (2005) *Functional Anatomy of the Spine - 2nd Ed*., Oxford: Butterworth-Heinemann.

Middleton, K.J., Mills, P.M., Elliott, B.C. and Alderson, J.A. (2016) The association between lower limb biomechanics and ball release speed in cricket fast bowlers: a comparison of high-performance and amateur competitors. *Sports Biomechanics*, 15(3), pp.357-369.

Mikula, A.L., Hetzel, S.J., Binkley, N. and Anderson, P.A. (2016). Clinical height measurements are unreliable: a call for improvement. *Osteoporosis International*, 27 (10) pp.3041-3047.

Miyazaki, J., Murata, S., Horie, J., Uematsu, A., Hortobágyi, T. and Suzuki, S. (2013). Lumbar lordosis angle (LLA) and leg strength predict walking ability in elderly males. *Archives of Gerontology and Geriatrics*, 56(1), pp.141–147.

Morton, S., Barton, C.J., Rice, S. and Morrissey, D. (2014). Risk factors and successful interventions for cricket-related low back pain: a systematic review. *British Journal of Sports Medicine*, 48(8), pp.685–691.

Mount, S., Moore, I. and Ranson, C. (2015, a) Bowlers are at greater risk of sustaining 'related', subsequent injuries than batters or wicket-keepers. *5th World Congress of Science and Medicine in Cricket 2015*: Luna Park, Sydney, 23-27 March.

Mount, S., Ranson, C. and Moore, I. (2015, b) Three-year cricket injury surveillance: fast bowlers are the biggest injury burden. *5th World Congress of Science and Medicine in Cricket 2015*: Luna Park, Sydney, 23-27 March.

Munster, M.M., Brismée, J.M., Sizer, P.S., Browne, K., Dewan, B., Litke, A., Pape, J.L. and Sobczak, S. (2019) Can 5 minutes of repetitive prone press-ups and sustained prone press-ups following a period of spinal loading reverse spinal shrinkage?, *Physiotherapy Theory and Practice*, 35(3), pp.259-267.

Muyor, J.M., López-Miñarro, P.A. and Alacid, F. (2011). Spinal Posture of Thoracic and Lumbar Spine and Pelvic Tilt in Highly Trained Cyclists. *Journal of Sports Science & Medicine*, 10(2), pp.355–361.

Muyor, J.M., López-Miñarro, P.A. and Alacid, F. (2013, b). The Relationship Between Hamstring Muscle Extensibility and Spinal Postures Varies with the Degree of Knee Extension. *Journal of Applied Biomechanics*, 29(6), pp.678–686.

Muyor, J.M., Sánchez-Sánchez, E., Sanz-Rivas, D. and López-Miñarro, P.A. (2013, a). Sagittal Spinal Morphology in Highly Trained Adolescent Tennis Players. *Journal of Sports Science & Medicine*,12(3), pp.588–593.

Negrete, R.J., Hanney, W.J., Pabian, P. and Kolber, M.J. (2013). Upper Body Push and Pull Strength Ratio in Recreationally Active Adults. *International Journal of Sports Physical Therapy*, 8(2), pp.138–144.

Nicolella, D.P., Torres-Ronda, L., Saylor, K.J. and Schelling, X. (2018). Validity and reliability of an accelerometer-based player tracking device. *PLOS ONE*, 13(2), p.e0191823.

Nielsen, R.O., Simonsen, N.S., Casals, M., Stamatakis, E. and Mansournia, M.A. (2020). Methods matter and the "too much, too soon" theory (part 2): what is the goal of your sports injury research? Are you describing, predicting or drawing a causal inference?. *British Journal of Sports Medicine*, d Epub ahead of print: (25th February 2020). doi:10.1136/ bjsports-2018-100245.

Nikkhoo, M., Kuo, Y., Hsu, Y., Khalaf, K., Haghpanahi, M., Parnianpour, M. and Wang, J. (2015). Time-dependent response of intact intervertebral disc – In Vitro and In-Silico study on the effect of loading mode and rate. *Engineering Solid Mechanics*, 3(1), pp.51–58.

Nilsson, C., Wykman, A. and Leanderson, J (1993) Spinal sagittal mobility and joint laxity in young ballet dancers A comparative study between first-year students at the Swedish Ballet School and a control group. *Knee Surgery, Sports Traumatology, Arthroscopy*, 1, pp.206-208.

Noakes, T.D. and Durandt, J.J. (2000) Physiological requirements of cricket. *Journal of Sports Sciences*, 18(12), pp.919-929.

Olivier, B., Stewart, A.V. and Mckinon, W. (2013). Side-to-side asymmetry in absolute and relative muscle thickness of the lateral abdominal wall in cricket pace bowlers. *South African Journal of Sports Medicine*, 25(3), pp.81–86.

Olivier, B., Stewart, A.V., Olorunju, S.A.S. and McKinon, W. (2015) Static and dynamic balance ability, lumbo-pelvic movement control and injury incidence in cricket pace bowlers. *Journal of Science & Medicine in Sport*, 18(1), pp.19–25.

Olivier, B., Taljaard, T., Burger, E., Brukner, P., Orchard, J., Gray, J., Botha, N., Stewart, A. and Mckinon, W. (2016) *Sports Medicine*, 46, pp.79–101

Orchard, J. (2002). Injuries in Australian cricket at first class level 1995/1996 to 2000/2001 * Commentary. *British Journal of Sports Medicine*, 36(4), pp.270–274.

Orchard, J., James, T., Kountouris, A. and Portus, M. (2010). Changes to injury profile (and recommended cricket injury definitions) based on the increased frequency of Twenty20 cricket matches. *Open Access Journal of Sports Medicine*, 1, pp.63–76.

Orchard, J., James, T., Portus, M.R., Kountouris, A. and Dennis, R. (2009) Fast bowlers in cricket demonstrate up to 3- to 4-week delay between high workloads and increased risk of injury. *American Journal of Sports Medicine*, 37(6), pp.1186–1192.

Orchard, J., Newman, D., Stretch, R., Frost, W., Mansingh, A. and Leipus, A. (2005). Methods for injury surveillance in international cricket. *Journal of Science and Medicine in Sport*, 8(1), pp.1–14.

Orchard, J.W. (2004). Lumbar spine region pathology and hamstring and calf injuries in athletes: is there a connection? *British Journal of Sports Medicine*, 38(4), pp.502–504.

Orchard, J.W., Blanch, P., Paoloni, J., Kountouris, A., Sims, K., Orchard, J.J. and Brukner, P. (2015). Cricket fast bowling workload patterns as risk factors for tendon, muscle, bone and joint injuries. *British Journal of Sports Medicine*, 49(16), pp.1064–1068.

Orchard, J.W., Kountouris, A. and Sims, K. (2016). Incidence and prevalence of elite male cricket injuries using updated consensus definitions. *Open Access Journal of Sports Medicine*, Volume 7, pp.187–194.

Orchard, J.W., Meeuwisse, W., Derman, W., Hägglund, M., Soligard, T., Schwellnus, M. and Bahr, R. (2020). Sport Medicine Diagnostic Coding System (SMDCS) and the Orchard Sports Injury and Illness Classification System (OSIICS): revised 2020 consensus versions. *British Journal of Sports Medicine*, 54(7), pp.397–401.

Orchard, J.W., Ranson, C., Olivier, B., Dhillon, M., Gray, J., Langley, B., Mansingh, A., Moore, I.S., Murphy, I., Patricios, J., Alwar, T., Clark, C.J., Harrop, B., Khan, H.I., Kountouris, A., Macphail, M., Mount, S., Mupotaringa, A., Newman, D. and O'Reilly, K. (2016). International consensus statement on injury surveillance in cricket: a 2016 update. *British Journal of Sports Medicine*, 50(20), pp.1245–1251.

Owens, S.C., Brismée, J.-M., Pennell, P.N., Dedrick, G.S., Sizer, P.S. and James, C.R. (2009). Changes in Spinal Height Following Sustained Lumbar Flexion and Extension Postures: A Clinical Measure of Intervertebral Disc Hydration Using Stadiometry. *Journal of Manipulative and Physiological Therapeutics*, 32(5), pp.358–363.

Paik, N.C., Lim, C.S. and Jang, H.S. (2013). Numeric and Morphological Verification of Lumbosacral Segments in 8280 Consecutive Patients. *Spine*, 38(10), pp.E573–E578.

Panjabi, M.M. (1992) The Stabilizing System of the Spine. Part II. Neutral Zone and Instability Hypothesis. Journal of Spinal Disorders, 5(4), pp.390-397.

Park, C.O. (1997). Diurnal variation in lumbar MRI: Correlation between signal intensity, disc height, and disc bulge. *Yonsei Medical Journal*, 38(1), p.8.

Payne, W., Carlson, J., Hoy, G. and Laussen, S.P. (1987) What research tells the cricket coach. *Sports Coach*, 10(4), pp.17-22.

Pennell, P.L., Owens, S.C. and Brismée, J.-M. (2012). Inter-tester and Intra-tester Reliability of a Clinically Based Spinal Height Measurement Protocol. *Journal of Spine*, 01(02). Pp.1-4.

Perrett, C., Lamb, P. and Bussey, M. (2020). Is there an association between external workload and lower-back injuries in cricket fast bowlers? A systematic review. *Physical Therapy in Sport*, 41, pp.71–79.

Petersen, C., Pyne, D., Portus, M. and Dawson, B. (2011) Comparison of player movement patterns between 1-day and test cricket. *Journal of Strength and Conditioning Research*, 25, pp.1368–1373.

Petersen, C., Pyne, D., Portus, M., Dawson, B. and Karpinnen, S. (2009) Variability in movement patterns during one day internationals by a cricket fast bowler. *International Journal of Sports Physiology Performance*, 4, pp.278–281.

Petersen, C., Pyne, D., Portus, M., Dawson, B. and Kellett, A. (2010) Movement patterns in cricket vary by both position and game format. *Journal of Sports Sciences*, 28, pp.45–52.

Pol, R., Hristovski, R., Medina, D. and Balague, N. (2018). From microscopic to macroscopic sports injuries. Applying the complex dynamic systems approach to sports medicine: a narrative review. *British Journal of Sports Medicine*, 53(19), pp.1214–1220.

Pooni, J., Hukins, D., Harris, P., Hilton, R. and Davies, K. (1986). Comparison of the structure of human intervertebral discs in the cervical, thoracic and lumbar regions of the spine. *Surgical and Radiologic Anatomy*, 8(3), pp.175–182.

Portus, M.R., Mason, B.R., Elliott, B.C., Pfitzner, M.C. and Done, R.P. (2004) Technique factors related to ball release speed and trunk injuries in high performance cricket fast bowlers. *Sport Biomechanics*, 3(2), pp.263–84.

Post, R.B. and Leferink, V.J.M. (2004). Spinal mobility: sagittal range of motion measured with the SpinalMouse, a new non-invasive device. *Archives of Orthopaedic and Trauma Surgery*, 124(3), pp.187–192.

Pourahmadi, M., Hesarikia, H., Ghanjal, A. and Shamsoddini, A. (2020). Psychometric Properties of the iHandy Level Smartphone Application for Measuring Lumbar Spine Range of Motion and Lordosis: A Systematic Review of the Literature. *Journal of Sport Rehabilitation*, 29(3), pp.352–359.

Prushansky, T., Geller, S., Avraham, A., Furman. C and Sela, L. (2013) Angular and linear spinal parameters associated with relaxed and erect postures in healthy subjects, *Physiotherapy Theory and Practice*, 29(3), pp.249-257.

Pyke, F.S., Crouch, G.C. and Davis, K.H. (1975). Case Report—The Testing and Training of an International Fast Bowler—Dennis Lillee. *British Journal of Sports Medicine*, 9(3), pp.152–154.

Rabal-Pelay, J., Cimarras-Otal, C., Alcázar-Crevillén, A., Planas-Barraguer, J.L and Bataller-Cervero, A.V. (2019) Spinal shrinkage, sagittal alignment and back discomfort changes in manufacturing company workers during a working day. *Ergonomics*, 62(12), pp.1534-1541.

Rago, V., Brito, J., Figueiredo, P., Krustrup, P. and Rebelo, A. (2020). Application of Individualized Speed Zones to Quantify External Training Load in Professional Soccer. *Journal of Human Kinetics*, 72(1), pp.279–289.

Ranson, C.A. (2007). *Lumbar MRI abnormalities and muscle morphology, trunk kinematics and lower back injury in professional fast bowlers in cricket*. [online] espace.curtin.edu.au. Available at: https://espace.curtin.edu.au/handle/20.500.11937/259 [Accessed 28 Jan. 2019].

Ranson, C.A., Burnett, A.F. and Kerslake, R.W. (2010). Injuries to the lower back in elite fast bowlers. *The Journal of Bone and Joint Surgery. British volume*, 92-B(12), pp.1664–1668.

Ranson, C.A., Burnett, A.F., King, M., Patel, N. and O'Sullivan, P.B. (2008) The relationship between bowling action classification and three-dimensional lower trunk motion in fast bowlers in cricket. *Journal Sports Sciences*,26(3), pp.267–76.

Ranson, C.A., Kerslake, R.W., Burnett, A.F., Batt, M.E. and Abdi, S. (2005) Magnetic resonance imaging of the lumbar spine in asymptomatic professional fast bowlers in cricket. *Journal of Bone Joint Surgery*. British volume, 87(8), pp.1111–1116.

Reilly, T. and Chana, D. (1994). Spinal shrinkage in fast bowling. *Ergonomics*, 37(1), pp.127–132.

Reilly, T. and Freeman, K.A. (2006). Effects of loading on spinal shrinkage in males of different age groups. *Applied Ergonomics*, 37(3), pp.305–310.

Reilly, T. Boocock, MG., Garbutt, G and Troup, JDG. (1988) Shrinkage in total body length: its measurement and application. *Human Biologia Budapest*, 18, pp.183-191.

Reilly, T., Tyrrell A.R. and Troup J.D.G. (1984) Orcadian Variation in Human Stature, The *Journal of Biological and Medical Rhythm Research*, 1(2), pp.121-126.

Ressman, J., Grooten, W.J.A. and Rasmussen Barr, E. (2019). Visual assessment of movement quality in the single leg squat test: a review and meta-analysis of inter-rater and intrarater reliability. *BMJ Open Sport & Exercise Medicine*, 5(1), p.e000541.

Ripani, M., Di Cesare, A., Giombini, A., Agnello, L., Fagnani, F. and Pigozzi, F. (2008), Spinal curvature: comparison of frontal measurements with the Spinal Mouse and radiographic assessments. *Journal of Sports Medicine & Physical Fitness*, 48, pp.488-494.

Rodacki, C.L., Fowler, N.E., Rodacki, A.L. and Birch, K. (2003). Stature loss and recovery in pregnant women with and without low back pain. *Archives of Physical Medicine and Rehabilitation*, 84(4), pp.507–512.

Rodacki, C.L.N., Fowler, N.E., Rodacki A.L.F. and Birch, K. (2001) Repeatability of measurement in determining stature in sitting and standing postures. *Ergonomics*, 44(12), pp.1076-1085.

Rodacki, C.L.N., Rodacki, A.F.L., Ugrinowitsch, C., Zielinski, D. and Budal da Costa, R. (2008). Spinal unloading after abdominal exercises. *Clinical Biomechanics*, 23(1), pp.8–14.

Roghani, T., Khalkhali, Z.M., Rahimi, A., Talebian, S., Dehghan, M.F., Akbarzadeh, B.A., King, N. and Katzman, W. (2017). The Reliability of Standing Sagittal Measurements of Spinal Curvature and Range of Motion in Older Women With and Without Hyperkyphosis Using a Skin-Surface Device. *Journal of Manipulative and Physiological Therapeutics*, 40(9), pp.685–691.

Rossi, J. S. (1990). Statistical power of psychological research: What have we gained in 20 years? *Journal of Consulting and Clinical Psychology, 58*(5), pp.646–656.

Ruddy, J.D., Cormack, S.J,, Whiteley, R., Williams, M.D., Timmins, R.G. and Opar, D.A. (2019) Modeling the Risk of Team Sport Injuries: A Narrative Review of Different Statistical Approaches. *Frontiers in Physiology,* 10 (829), pp.1-16.

Salo, A. and Grimshaw, P.N. (1998) An examination of the kinematic variability of motion analysis in sprint hurdles. *Journal of Applied Biomechanics*, 14, pp211-222.

Schmidt, H., Kettler, A., Heuer, F., Simon, U., Claes, L. and Wilke, H.J. (2007) Intradiscal Pressure, Shear Strain, and Fiber Strain in the Intervertebral Disc Under Combined Loading. *Spine*, 32(7), pp.748-755.

Schousboe, J.T., Paudel, M.L., Taylor, B.C., Virnig, B.A., Cauley, J.A., Curtis, J.R. and Ensrud, K.E. (2012). Magnitude and consequences of misclassification of incident hip fractures in large cohort studies: the Study of Osteoporotic Fractures and Medicare claims data. *Osteoporosis International*, 24(3), pp.801–810.

Scott, T.J., Black, C.R., Quinn, J. and Coutts, A.J. (2013). Validity and Reliability of the Session-RPE Method for Quantifying Training in Australian Football. *Journal of Strength and Conditioning Research*, 27(1), pp.270–276.

Senck, S., Trieb, K., Kastner, J., Hofstaetter, S.G., Lugmayr, H. and Windisch, G. (2019). Visualization of intervertebral disc degeneration in a cadaveric human lumbar spine using microcomputed tomography. *Journal of Anatomy*, 236(2), pp.243–251.

Senington, B., Lee, R.Y. and Williams, J.M. (2018) Are shoulder counter rotation and hip shoulder separation angle representative metrics of three-dimensional spinal kinematics in cricket fast bowling? *Journal of Sports Sciences*, 36(15), pp.1763–7.

Senington, B., Lee, R.Y. and Williams, J.M. (2020). Biomechanical risk factors of lower back pain in cricket fast bowlers using inertial measurement units: a prospective and retrospective investigation. *British Medical Journal: Open Sport & Exercise Medicine*, 6(1), pp.e000818.

Shacklock, M. (2005). *Clinical Neurodynamics: A New System of Neuromusculoskeletal Treatment*. Elsevier Health Sciences: Oxford, England.

Sheeran, L., Sparkes, V., Busse, M. and van Deursen, R. (2009). Preliminary study: reliability of the spinal wheel. A novel device to measure spinal postures applied to sitting and standing. *European Spine Journal*, 19(6), pp.995–1003.

Sholto-Douglas, R., Cook, R., Wilkie, M. and Christie, C.J.-A. (2020). Movement Demands of an Elite Cricket Team During the Big Bash League in Australia. *Journal of Sports Science & Medicine*, 19(1), pp.59–64.

Sims, K., Kountouris, A., Orchard, J., Beakley, D. and Saw, A. (2017). The relationship between cricket fast bowling workload and lumbar stress fracture. *Journal of Science and Medicine in Sport*, 20, p.41.

Sims, K., Portus, M., Pfitzner, M., Farhart, P. and Orchard, J. (2010) Links between musculoskeletal screening and lower back/lower limb injury in Australian first class cricketers: A 3 year prospective study. *Journal of Science and Medicine in Sport, Supplement 2,* pp.e43-e44.

Sobczak, S., Dugailly, P.-M., Gilbert, K.K., Hooper, T.L., Sizer, J., James, C.R., Poortmans, B., Matthijs, O.C. and Brismée, J.-M. (2016). Reliability and validation of in vitro lumbar spine height measurements using musculoskeletal ultrasound: A preliminary investigation. *Journal of Back and Musculoskeletal Rehabilitation*, 29(1), pp.171–182.

Soomro, N., Strasiotto, L., Sawdagar, T., Lyle, D., Mills, D., Ferdinands, R. and Sanders, R. (2018). Cricket Injury Epidemiology in the Twenty-First Century: What is the Burden? *Sports Medicine*, 48(10), pp.2301–2316.

Steele, J., Bruce-Low, S., Smith, D., Jessop, D. and Osborne, N. (2016). Determining the reliability of a custom built seated stadiometry set-up for measuring spinal height in participants with chronic low back pain. *Applied Ergonomics*, 53, pp.203–208.

Stockhill, N. and Bartlett, R. (1996). Possible errors in measurement of shoulder alignment using 3-D cinematography. In J. Abrantes (Ed.), *Proceedings of the XIVth International Symposium on Biomechanics in Sport* (pp. 209 – 212). Portugal: Edicoes.

Stothart, J.P. and McGill, S.M. (2000) Stadiometry: on measurement technique to reduce variability in spine shrinkage measurement. *Clinical Biomechanics*, 15, pp.546-548.

Stretch, R.A. (2001). Incidence and nature of epidemiological injuries to elite South African cricket players. *South African Medical Journal*, 91(4), pp.336–339.

Stretch, R.A. (2003). Cricket injuries: a longitudinal study of the nature of injuries to South African cricketers * Commentary. *British Journal of Sports Medicine*, 37(3), pp.250–253.

Stuelcken, M.C., Ginn, K.A. and Sinclair, P.J. (2008). Musculoskeletal profile of the lumbar spine and hip regions in cricket fast bowlers. *Physical Therapy in Sport*, 9(2), pp.82–88.

Todd, C.M., Agnvall, C., Kovac, P., Sward, A., Johansoon, C., Sward, L., Karlsson, J. and Baranto, A. (2015). Validation of spinal sagittal alignment with plain radiographs and the Debrunner Kyphometer. *Medical Research Archives*, 2(1).

Tomaszewski, K.A., Saganiak, K., Gladysz, T. and Walocha, J. (2015). The biology behind the human intervertebral disc and its endplates. *Folio Morphologica*, 74(2), pp.157-168.

Topalidou, A., Tzagarakis, G., Souvatzis, X., Kontakis, G. and Katonis, P. (2014). Evaluation of the reliability of a new non-invasive method for assessing the functionality and mobility of the spine. *Acta of Bioengineering and Biomechanics*, 16,(1), pp.117-124.

Troup, J.D. (1976) Mechanical factors in spondylolisthesis and spondylolysis. *Clinical Orthopaedics and Related Research*, 117, pp.59-67.

Tyrrell, A.R., Reilly, T. and Troup, J.D.G. (1985) Circadian variation in stature and the effects of spinal loading. *Spine*, 10, pp.161-164.

Tysoe, A., Moore, I.S., Ranson, C., McCaig, S. and Williams, S. (2020). Bowling loads and injury risk in male first class county cricket: Is "differential load" an alternative to the acute-to-chronic workload ratio?. *Journal of Science and Medicine in Sport*. pp.1-5

van der Veen, A.J., Mullender, M.G., Kingma, I., van, J.H. and Smit, T.H. (2008). Contribution of vertebral bodies, endplates, and intervertebral discs to the compression creep of spinal motion segments. *Journal of Biomechanics*, 41(6), pp.1260–1268.

van Deursen, L.L., van Deursen, D.L., Snijders, C.J. and Wilke, H.J. (2005). Relationship between everyday activities and spinal shrinkage. *Clinical Biomechanics*, 20(5), pp.547–550.

Van Dieen, J.H. and Toussaint, H.M. (1993) Spinal shrinkage as a parameter of functional load. *Spine,* 18(11), pp.1504-1514.

van Mechelen, W., Hlobil, H. and Kemper, H.C.G. (1992). Incidence, Severity, Aetiology and Prevention of Sports Injuries. *Sports Medicine*, 14(2), pp.82–99.

Vandlen, K.A., Marras. W.S. and Mendelsohn, D. (2012) A nonlinear contact algorithm predicting facet joint contribution in the lumbar spine of a specific person. *Theoretical Issues in Ergonomics Science*, 13(3), pp.303-317.

Vickery, W., Dascombe, B. and Duffield, R. (2017). The Association Between Internal and External Measures of Training Load in Batsmen and Medium-Fast Bowlers During Net-Based Cricket Training. *International Journal of Sports Physiology and Performance*, 12(2), pp.247–253.

Vickery, W., Dascombe, B.J. and Scanlan, A. T. (2018) A review of the physical and physiological demands associated with cricket fast and spin bowlers. *Sports Science & Coaching*, 13(2), pp.290-301.

Vickery, W., Duffield, R., Crowther, R., Beakley, D., Blanch, P. and Dascombe, B.J. (2018). Comparison of the Physical and Technical Demands of Cricket Players During Training and Match-Play. *Journal of Strength and Conditioning Research*, 32(3), pp.821–829.

Voss, L.D. and Bailey, B.J. (1994). Equipping the community to measure children's height: the reliability of portable instruments. *Archives of Disease in Childhood*, 70(6), pp.469–471.

Voss, L.D., Bailey, B.J., Cumming, K., Wilkin, T.J. and Betts, P.R. (1990). The reliability of height measurement (the Wessex Growth Study). *Archives of Disease in Childhood*, 65(12), pp.1340–1344.

Vrtovec, T., Pernuš, F. and Likar, B. (2009). A review of methods for quantitative evaluation of spinal curvature. *European Spine Journal*, 18(5), pp.593–607.

Vrtovec, T., Pernuš, F. and Likar, B. (2009). A review of methods for quantitative evaluation of spinal curvature. *European Spine Journal*, 18(5), pp.593–607.

Wang, C., Vargas, J.T., Stokes, T., Steele, R. and Shrier, I. (2020). Analyzing Activity and Injury: Lessons Learned from the Acute:Chronic Workload Ratio. *Sports Medicine*.

Warren, A., Williams, S., McCaig, S. and Trewartha, G. (2018). High acute:chronic workloads are associated with injury in England & Wales Cricket Board Development Programme fast bowlers. *Journal of Science and Medicine in Sport*, 21(1), pp.40–45.

Warren, A., Williams, S., McCaig, S. and Trewartha, G. (2018). High acute:chronic workloads are associated with injury in England & Wales Cricket Board Development Programme fast bowlers. *Journal of Science and Medicine in Sport*, 21(1), pp.40–45.

Webster, T.M., Comfort, P. and Jones P.A. (2020) Relationship Between Physical Fitness and the Physical Demands of 50-Over Cricket in Fast Bowlers. Journal of Strength and Conditioning Research, 00(00), pp.1-7.

Wilby, J., Linge, K., Reilly, T. and Troup, J.D.G. (1987) Spinal shrinkage in females: circadian variation and effects of circuit weight training. *Ergonomics*, 30, pp.47-54.

Wilke, H.-J., Neef, P., Hinz, B., Seidel, H. and Claes, L. (2001). Intradiscal pressure together with anthropometric data – a data set for the validation of models. *Clinical Biomechanics*, 16, pp.S111–S126.

Windt, J. and Gabbett, T.J. (2016). How do training and competition workloads relate to injury? The workload—injury aetiology model. *British Journal of Sports Medicine*, 51(5), pp.428–435.

Windt, J., Ardern, C.L., Gabbett, T.J., Khan, K.M., Cook, C.E., Sporer, B.C. and Zumbo, B.D. (2018). Getting the most out of intensive longitudinal data: a methodological review of workload–injury studies. *BMJ Open*, 8(10), p.e022626.

Winter, D. A. (1990). *Biomechanics and motor control of human movement*. New York: Wiley.

Worthington, P., King, M. and Ranson, C. (2013) The influence of cricket fast bowlers' front leg technique on peak ground reaction forces, *Journal of Sports Sciences*, 31:4, pp.434-441.

Appendix 1

Participant Information Sheet

About the study

Fast bowlers are prone to injury. Previous research has focussed on the type of bowling action and the amount of overs bowled. This research aims to add the measure of how much you shrink when you bowl and the curves of your spine. We all shrink about 20mm in a day due to the loss of fluid from the discs in your spine and loads placed upon them. You can imagine the discs act like a really stiff sponge so when you lose fluid and they get slightly squashed. Fortunately when you lie down at night the water moves back in and they go back to their original shape. The aim of the research is to see how bowling five overs affects the curvature (using the The Spinal Mouse) of your spine and shrinkage of the discs by measuring stature (height) loss (using the Seca 287 Stadiometer). You will also have your bowling action filmed so a biomechanical analysis can be undertaken.

Some questions you may have about the research project:

Why have you asked me to take part and what will I be required to do?

You have been asked to take part as you are an elite fast bowler. On one day you will have spinal shrinkage and curvature measured before and on completion of 5 overs of fast bowling. In between deliveries you will undertake normal walking activities as if you were fielding at fine-leg/third-man. You will have three deliveries filmed to analyse the biomechanics of your action. The testing may take up to one and half hours to complete.

What if I do not wish to take part or change my mind during the study?

Your participation in the study is entirely voluntary. You are free to withdraw from the study at any time without having to provide a reason for doing so.

What happens to the research data?

Data collected will be anonymous and remain confidential. The data will be stored in a password protected file on a personal computer, held in accordance with University regulations. You will be able to request your results once all testing is finished. The lead researcher Tim Barry and his supervisory team at Manchester Metropolitan University will have access to the data.

How will the research be reported?

My research will be presented as a PhD thesis. I hope to be able to publish the data in peer reviewed journals and presented at the World Congress of Science and Medicine in Cricket. If you would like a copy of my papers I will be willing to send them to you on request.

How can I find out more information?

Please contact Tim Barry directly. Tel Number : 07798 650030

e- mail: t.j.barry1@lancaster.ac.uk

Address: Lancaster University, Lancaster, LA1 4YW.

What if I want to complain about the research

Initially you should contact the researcher directly. However, if you are not satisfied or wish to make a more formal complaint you should contact Manchester Metropolitan University Research Office on 0161 247 2000.

Appendix 2

Participant Consent Form

Please answer the following questions by circling your responses:

Have you read and understood the information sheet about this study? YES NO

Have you been able to ask questions and had enough information? YES NO

Do you understand that you are free to withdraw from this study at any time, and without having to give a reason for withdrawal? YES NO

Your responses will be anonymised. Do you give permission for members of the research team to analyse and quote your anonymous responses? YES NO

Please sign here if you wish to take part in the research and feel you have had enough information about what is involved:

Signature of participant:.. **Date:**................

Signature of Parent /Guardian for Participants U18

……………………………………………………………………………… **Date:** ………….

Name (block letters):..

Publications

Barry, T. & Jackson, S. (2015) Spinal shrinkage and lateral flexion during eight overs of fast bowling. *5th World Congress of Science and Medicine in Cricket*. Luna Park, Sydney, Australia, 23 - 27 March.

Barry, T. & Traves, B. (2015) Spine morphology in sagittal and frontal planes in fast bowlers pre- and post-8 overs of fast bowling using a novel skin surface measuring device. *5th World Congress of Science and Medicine in Cricket*. Luna Park, Sydney, Australia, 23 - 27 March.