THE CRICKETING SHOULDER: BIOMECHANICS AND ANALYSIS OF POTENTIAL INJURY RISK FACTORS TO THE SHOULDER IN ELITE CRICKETERS

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DECLARATION

I, Megan Dutton, hereby declare that the work on which this dissertation is based is my original work (except where acknowledgements indicate otherwise) and that neither the whole work nor part of it has been, is being, or is to be submitted for another degree in this or any other university.

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PERMISSION TO INCLUDE PUBLICATIONS IN THIS DOCTORAL THESIS

I confirm that I have been granted permission by the University of Cape Town's Doctoral Degrees Board to include the following publication(s) in my thesis, and where co-authorships are involved, my co-authors have agreed that I may include the publications:

1. **Dutton, M.**, Tam, N., Gray, J. (2019) The incidence and impact of time-loss and non-time-loss shoulder injury in elite South African cricketers: A one-season, prospective cohort study. *Journal of Science and Medicine in Sport.* https://doi.org/10.1016/j.jsams.2019.05.006
2. **Dutton, M.**, Tam, N., Brown, J.C., Gray, J. (2019) The cricketer's shoulder: Not a classic throwing shoulder. *Physical Therapy in Sport.* 37:120-127
3. **Dutton, M.**, Gray, J., Prins, D., Divekar, N., Tam, N. (submitted 10 April 2019) Overhead throwing in cricketers: A biomechanical description and playing level considerations. *Journal of Sports Sciences*

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Finally, to my family, I thank you for challenging and inspiring me to grow and be better daily. To my dad, Dr Chris Dutton, you have been a prestigious example to us all and I wish to dedicate this thesis to you.

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ABSTRACT

Historically, cricketing literature has explored the disciplines of bowling and batting, with fielding receiving little attention until its importance was highlighted by the introduction of T20 matches. The novelty of this research lies in its clinically meaningful contribution to understanding shoulder injury aetiology in cricketers as overhead throwing athletes. The studies included in this thesis investigate the musculoskeletal profile of a cricketer's shoulder, as well as the intrinsic factors associated with shoulder injury risk. Further, the influence of some of these risk factors on the cricketers' overhead throwing biomechanics is explored and intend to improve the development of cricket-specific shoulder injury prevention programmes.

An overview of the literature (Chapter 2) includes the epidemiology of shoulder injuries in cricketers; as well as a description of overhead throwing kinematics and the musculoskeletal adaptations associated with overhead throwing in cricket, compared to baseball, which has the greatest volume of throwing related studies. Based on previous outdated definitions of injury and not the current consensus definitions, shoulder injuries in cricket have been reported to occur infrequently. Various injury surveillance studies have identified time-loss shoulder injuries in cricketers, yet none have considered non-time-loss shoulder injuries. Although a limited number of studies have proposed potential intrinsic risk factors to shoulder injury in cricketers, no associations have been found. However, the cricketer's shoulder is prone to injury due to the high forces generated while repeatedly throwing overhead during fielding. While overhead throwing biomechanics has been well investigated in baseball, minimal research exists for cricket. In addition, the understanding of throwing biomechanics in cricket has relied on two-dimensional motion analysis that is known to be insufficient for the analysis of rotational kinematics and kinetics.

Elite (senior national and franchise) cricketers were recruited for this study. This study consisted of two parts. During the first part of the thesis demographic, training, competition and injury history data were obtained; and a shoulder-specific functional questionnaire and pre-season shoulder screening protocol were performed, prior to annual musculoskeletal screening. The incidence of all shoulder injuries were recorded throughout a six month cricket season. A profile of pertinent risk factors was assessed. The second part of the thesis evaluated throwing biomechanics of cricketers. Upper quarter, spinal, pelvic and hip kinematics, as well as shoulder and elbow kinetics were measured during the execution of overhead throwing from a stationary position, and with a run-up.

This thesis includes three original papers and two experimental Chapters. The first paper (Chapter 3) documents the incidence of non-time-loss shoulder injuries in elite South African cricketers. Overall, the incidence of shoulder injury in cricketers during the 2016/2017 season was 18%, described as 5% time-loss and 13% non-time-loss injuries. Primary skill and fielding were negatively impacted in 100% and 80% of cricketers who sustained non-time-loss shoulder injuries, respectively. The entire cricket cohort recorded low scores on the shoulder-specific questionnaire, completed pre- and post-season, irrespective of injury history or injury sustained during the 2016/2017 season indicating a generalised reduction in the level of function in overhead activity.

Paper 2 (Chapter 4) provides a description of the musculoskeletal profile of a cricketer's shoulder which is atypical to the *"thrower's paradox"* described in baseball. Specifically, cricketers present with a loss in total glenohumeral (GH) rotational range of motion (ROM), GH internal rotation deficit (GIRD) in the absence of external rotation gain (ERG); and global weakness of the rotator cuff and scapula stabilising muscles. Further, dominant shoulder supraspinatus tendon (SsT) thickness ≥5.85mm (sensitivity: 72%, specificity: 63%) and non-dominant pectoralis minor length (PML) ≤12.85cm (sensitivity: 83%, specificity: 55%) predicted seasonal dominant shoulder injury ($p<0.05$). From the findings indicated in Papers 1 and 2 (Chapters 3 and 4) it can be postulated that cricketers are generally a high-risk population for shoulder injury, amongst overhead throwing athletes, due to the lack of shoulder-specific musculoskeletal adaptation frequently observed in other overhead throwing populations.

Paper 3 (Chapter 5) and experimental Chapters 6 and 7 investigate the kinematics and kinetics of overhead throwing from a stationary position, with a run-up and the consequence of GIRD in these two throwing approaches. A kinematic description of overhead throwing in cricket is provided and compared to baseball overhead pitching, in Paper 3 (Chapter 5). Maximum external rotation (MER) was regarded as the most critical point for potential shoulder injury in cricketers when throwing overhead from a stationary position. Further, a comparison between playing levels highlighted that amateur cricketers may display an increased risk for shoulder injury at MER as these cricketers were found to have decreased elbow flexion ROM in 2-14% of the throwing cycle ($p=0.01$), as well as greater shoulder ($p=0.021$) and elbow ($p=0.043$) compression and increased superior shoulder force ($p=0.022$) at MER, when compared to elite cricketers.

Findings from experimental Chapter 6 indicate that when throwing with a run-up (dynamic) increased lumbo-pelvic ($p=0.02$) and hip flexion ($p=0.01$) occur sporadically in the throwing cycle, compared to throwing from a stationary position (static). In addition, increased shoulder compression (p=0.02) and posterior force (p=0.009) occur at MER, while reduced superior shoulder force (p=0.005) and elbow compression (p=0.03), superior (p=0.002) and medial (p=0.03) forces occur at ball release (BR), when throwing dynamically versus statically. These two Chapters highlight MER as the most critical point for potential shoulder injury in cricketers, which may further be attenuated by the absence of ERG, level of play and throwing from a stationary position while fielding.

Experimental Chapter 7 investigated and highlights the potential correlations between GIRD, a frequently described risk factor for overhead athletes, and the other musculoskeletal variables measured, as well as overhead throwing biomechanics from a stationary and run-up approach. Greater GIRD was associated with reduced passive hip external rotation ROM on the dominant side (p<0.03), measured by inclinometer. In addition, increased GIRD was associated with reduced dominant hip abduction ROM during 0-23% of the throwing cycle (p=0.002), and superior shoulder force (p<0.004) and elbow compression (p<0.009), when throwing from a stationary position. Finally, greater GIRD was associated with increased posterior shoulder force at maximum internal rotation (MIR), when throwing from a stationary position (p<0.013) and with a run-up (p<0.03). These findings suggest that GIRD may negatively influence ball velocity specifically when cricketers attempt to throw overhead from a stationary position. Further, it is postulated that when throwing overhead (irrespective of approach) cricketers may overcome the mechanical insufficiency of GIRD by actively engaging the dominant hip internal rotators, to prematurely rotate the pelvis forward, in order to generate sufficient ball velocity. This may result in cricketers employing a throw across the body, which when repeatedly performed may cause hypertrophy of the dominant hip internal rotators, thereby reducing passive hip external rotation ROM. This biomechanical adaptation to GIRD may contribute to the cricketer’s predisposition for shoulder injury when throwing overhead, or may occur in an attempt to protect the shoulder against further injury.

In conclusion, the inherent musculoskeletal profile of this elite cricketing cohort’s shoulder increases injury risk, particularly when throwing overhead. There is a need to investigate the influence of throwing volume, duration of season and player speciality on the musculoskeletal profile of the shoulder and concomitant injury in cricket. It is suggested that modifiable intrinsic factors found to be associated with shoulder injury and the performance of overhead throwing should be appropriately incorporated into injury prevention or pre-season conditioning programmes, to reduce the occurrence of injury. Further research should determine the efficacy of these programmes on shoulder injury prevention and throwing performance, in cricketers.

PREFACE

This doctoral project enabled me to enhance my knowledge, broaden my clinical reasoning and challenged me in the areas of research and academia. The experiences gained throughout the last three and a half years have been exceptionally rewarding. The following list of publications, conference presentations and clinical applications represent the academic contribution achieved by this thesis, thus far.

Journal submissions

1. **Dutton M.**, Tam N., Gray J. Incidence and impact of time-loss and non-time-loss shoulder injuries in elite South African cricketers: A one-season, prospective cohort study. *Journal of Science and Medicine in Sport.* 2019. https://doi.org/10.1016/j.jsams.2019.05.006
2. **Dutton M.**, Tam N., Brown J.C., Gray J. The cricketer's shoulder: Not a classic throwing shoulder. *Physical Therapy in Sport.* 2019. 37, 120-127. https://doi.org/10.1016/j.ptsp.2019.03.014
3. **Dutton M.**, Gray J., Divekar N., Prins D., Tam N. (submitted 2019) Overhead throwing in cricketers: A biomechanical description and playing level considerations. *Journal of Sport Sciences* (under review).

Conference Presentations

1. **Dutton M.** A descriptive overview of the pre-season shoulder in elite professional cricketers. Orthopaedic Research Unit Symposium, University of Cape Town. September 2016.
2. **Dutton M.** Taking wickets with a healthy shoulder. South African Sports Medicine Association Conference. Cape Town. October 2017.
3. **Dutton M.** Overhead throwing shoulder adaptations: Baseball vs. Cricket. South African Society of Physiotherapy. Sports Interest Group, Annual General Meeting. Cape Town. April 2018.
4. **Dutton M.**, Tam N., Roche S., Gray J. Shoulder pain in cricket: An under-reported injury. South African Orthopaedic Association Congress. Council for Scientific and Industrial Research, Pretoria. September 2018.
5. **Dutton M.**, Tam N., Brown J.C., Gray J. The cricketers shoulder: Not a classic throwing shoulder. The 6th World Congress of Science and Medicine in Cricket. Loughborough, United Kingdom. July 2019.
6. **Dutton M.**, Gray J., Divekar N., Prins D., Tam N. Do cricketers display similar overhead throwing biomechanics to baseball players? The 6th World Congress of Science and Medicine in Cricket. Loughborough, United Kingdom. July 2019.

Clinical Applications

1. Super 6: Preventative exercises for the shoulder (developed in collaboration with Cricket South Africa). 2017 (Figure 8.4, pg. 111)
2. Infographic: The cricketer's shoulder: Not a classic thrower's shoulder. 29 April 2019. (Figure 8.2, pg. 110)
3. Infographic: Overhead throwing biomechanics in cricketers. 29 April 2019. (Figure 8.3, pg. 111)

CONTRIBUTIONS OF AUTHORS TO THE THESIS

As part of the declaration of this thesis, I acknowledge contributions by various individuals to this work as detailed below:

The experimental design, data collection and analysis for all work were devised by myself[a], in conjunction with my supervisors, Dr Janine Gray[a,b] and Dr Nicholas Tam[a,c].

Dr James Brown[d,e] assisted with statistical analysis of the manuscript titled: *"The cricketer's shoulder: Not a classic throwing shoulder"* as more complex statistical procedures were applied. Statistical analysis of all other papers and experimental Chapters was performed in conjunction with Dr Janine Gray[a,b] and Dr Nicholas Tam[a,c].

Kinematic data collection, the development of the calibration frame and initial camera mounting were done by Mr. Nikhil Divekar[f], Ms. Danielle Prins[a] and myself[a].

Original algorithms for the kinematic Chapters in this thesis were written by Mr. Nikhil Divekar[f].

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LIST OF ABBREVIATIONS

AHD	Acromiohumeral distance
ANOVA	Analysis of variance
AUC	Area under curve
BR	Ball release
CI	Confidence interval
CV	Coefficient of variance
ER	External rotation
ERG	External rotation gain
GH	Glenohumeral Joint
GHER	Glenohumeral external rotators
GHIR	Glenohumeral internal rotators
GIRD	Glenohumeral internal rotation deficit
GM	Gluteus medius muscle
HREC	Human Research Ethics Committee
ICD	International Statistical Classification of Disease and Related Health Problems
IR	Internal rotation
KJOC	Kerlan-Jobe Orthopaedic Clinic Shoulder and Elbow Score
LT	Lower trapezius muscle
MER	Maximum external rotation
MIR	Maximum internal rotation
Nm	Newton metres
PML	Pectoralis minor muscle length
PSC	Posterior shoulder capsule
r	Correlation coefficient

RoC	Receiver operating curve
ROM	Range of motion
RR	Relative risk
SA	Serratus anterior muscle
SEM	Standard error of measurement
SPM	Statistical parametric mapping
SsT	Supraspinatus tendon thickness
T20	Twenty-twenty limited over cricket match
TROM	Total range of motion
UT	Upper trapezius muscle
WHO	World Health Organisation

INTRODUCTION

CHAPTER 1 – INTRODUCTION:

BACKGROUND AND OVERVIEW

1.1. BACKGROUND

The game of cricket is played between two teams of 11 players across a variety of match formats including, single innings 20 (T20) or 50 (one-day) overs per side, and multiple innings over four or five days (also known as a Test).[1,2] At any given time, one team will have two batsmen on the field, while the other will have one cricketer bowling and the remaining ten, fielding. The aim of the batting team is to score as many runs as possible, whereas the bowling/fielding team attempts to limit the number of runs scored and dismiss 10 of the 11 batsmen. Batsmen are dismissed if the ball bowled dislodges the bails of the wicket; and fielders either catch a ball in flight or run the batsmen out. The latter is achieved by fielders collecting the ball after it is struck by the batsman and returning it as quickly as possible to the bowler/fielder manning the stumps, who then dislodges the bails.[1,2] This method is also used to limit the runs scored by batsmen. Consequently, fielders are required to throw with speed and accuracy,[1] often in an unstable body position. All players are required to participate in throwing and fielding.

Throwing is a complex skill which requires several physical attributes to maximise ball velocity. It is estimated that an elite level cricketer performs an average of 44 throws per day.[3] Each throw may subject the shoulder to 550-1200 N (from half to full body weight) of force from maximum external rotation (MER) to arm deceleration.[4] Consequently, the development of shoulder pain in cricketers is thought to often occur as a result of an impingement mechanism that develops in response to the repetitive overuse and overload associated with throwing.[5,6]

Repetitive overhead throwing causes the anterior glenohumeral (GH) capsule to stretch and posterior capsuloligamentous and muscular complex to shorten.[7] In addition, bony remodelling of the humeral neck has been described in young throwers.[7-9] These anatomical adaptations alter the 180° arc of GH rotation to increase external rotation with a simultaneous decrease in internal rotation; an adaptation which can increase the ball velocity generated when throwing overhead.[10,11] When GH internal rotation ROM decreases beyond the concomitant increase in external rotation ROM (reduction in total GH rotational ROM <180°), a condition called glenohumeral internal rotation deficit (GIRD) occurs.[8]

Alongside the appearance of GIRD, soft tissue adaptations also occur in response to overhead throwing that promotes excessive anterio-superior humeral head migration,[12,13] leading to the development of shoulder impingement and pain.[7,14-16] Further, the kinematic deficiency of GIRD when throwing overhead has been associated with an increased risk of GH labral tears and rotator cuff strains, in baseball pitchers.[8,17-20]

It is important to note that throwing should be fluid motion and deficiencies in the kinematics and kinetics of the proximal (lower limbs and core) and distal (shoulder, elbow and hand of the throwing arm) kinetic chain may lead to injury or impaired throwing performance.[17] In addition to GIRD, numerous deficiencies have been found which negatively impact the shoulder when pitching/throwing overhead. These include restricted hip rotation[17,18,20,21]; poor hip abductor strength,[18,20,22] lumbar hyperlordosis[17,20] and reduced elbow flexion.[17,18,23-25]

1.2. KEY RESEARCH AREAS OF FOCUS

A paucity of knowledge and research exists for shoulder injuries in both elite South African and international cricketers. Sports injury research requires that injury incidence and severity is determined, prior to establishing aetiology and the risk factors or mechanisms associated with injury[26] (Figure 1.1). Therefore, to broaden the understanding of the impact cricket has on the shoulder joint, particular focus should be given to exploring the incidence and risk factors of shoulder injuries; overhead throwing biomechanics and the influence of musculoskeletal profiles on overhead throwing, in cricketers.

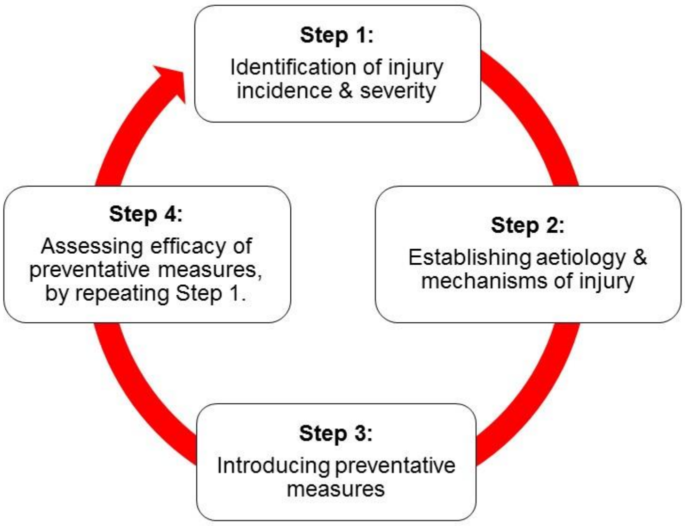


Figure 1.1: van Mechelen's model of sports injury research[26].

1.2.1 Shoulder Injury in Elite Cricketers

Interestingly, long-term injury surveillance studies report that shoulder injuries account for a mere five to seven percent of total injury complaints sustained by elite South African cricketers.[27-30] Thus, based on studies conducted in other major cricketing countries which adapted the definition of shoulder pain/injury used in self-report questionnaires to incorporate both time-loss and non-time-loss injuries, it is suggested that between 15-36% of South African cricketers may experience some form of seasonal shoulder pain and injury.[7,31,32]

Predictably, the incidence of shoulder pain in cricketers is greatest when throwing overhead.[6,27-29,31,33] Shoulder pain and/or injury have been found to most commonly affect the rotator cuff musculature and/or tendons.[27-30,34] Currently, cricket literature has only investigated the potential association between shoulder pain and alterations in GH rotational ROM[7] or scapula positioning.[32] To date, the musculoskeletal profile of a cricketer's shoulder has yet to be described. Further, no musculoskeletal risk factors have been found to be predictive of shoulder injury in cricket.

1.2.2 Comprehensive Understanding of Overhead Throwing in Cricket

Anecdotally, much of the biomechanical input to cricket fielding, specifically throwing, is drawn from the plethora of overhead pitching research conducted in baseball.[10,17-19,21,35] However, it is unknown if this is appropriate as cricketers rarely throw from a stationary position when fielding.[36]

The available research of overhead throwing biomechanics in cricket is sparse. Extant literature provides only two-dimensional kinematic descriptions from wind-up to ball release (BR) when throwing from a variety of approach angles.[1,37-39] The kinematics from the point of BR to arm deceleration, as well as the kinetics about the upper limb in cricket overhead throwing have not been investigated.

1.2.3 Musculoskeletal Adaptations Associated with Overhead Throwers

Presently, it is unknown whether cricketers display the same musculoskeletal adaptations which contribute to the shift in GH rotational arc of movement inherently found in baseball pitching shoulders.[40,41] Subsequently, the potential influence of the musculoskeletal profile of a cricketer's shoulder, specifically GIRD, on overhead throwing biomechanics, has not been described.

1.3. THESIS OVERVIEW

The research presented in this thesis comprises eight Chapters designed to understand the impact of cricket on the shoulder joint in elite South African cricket. This is the first broad investigation of all (time-loss and non-time loss) cricket related dominant shoulder injuries, associated risks and overhead throwing biomechanics among cricketers. The PhD thesis presents the results in three parts (Figure 1.2):

Part 1: Risk factors for shoulder injury (Chapters 3 and 4)

Part 2: Biomechanics of overhead throwing (Chapters 5 and 6)

Part 3: Musculoskeletal influence of the shoulder on overhead throwing biomechanics (Chapter 7)

Experimental Chapters 3-7 in this thesis is structured as a formal research manuscript for a peer-review journal and includes an abstract, introduction, methods, results, discussion and conclusion. Manuscripts which have been originally published (Chapter 3 and 4); and submitted, awaiting review (Chapter 5) are included in the relevant Chapters.

In preparation for the prospective longitudinal cohort studies of the thesis, a review of the literature on the epidemiology of shoulder injuries in cricketers, overhead throwing biomechanics and the musculoskeletal adaptations known to occur in response to repetitive overhead throwing is presented in Chapter 2. This is followed by a paper investigating the incidence of all (time-loss and non-time-loss) shoulder injuries in elite cricketers (Chapter 3). A description of the musculoskeletal profile of the cricketers shoulder and identification of the intrinsic factors associated with shoulder injury is presented in Chapter 4. The cricketer's overhead throwing biomechanics from a stationary position is described and the differences between playing levels considered, in Chapter 5. A kinematic and kinetic comparison of overhead throwing performed from stationary position and with a run-up is presented in Chapter 6. The effect of GIRD on overhead throwing biomechanics, irrespective of approach, is investigated in Chapter 7. The summary and conclusion section will complete this thesis in Chapter 8.

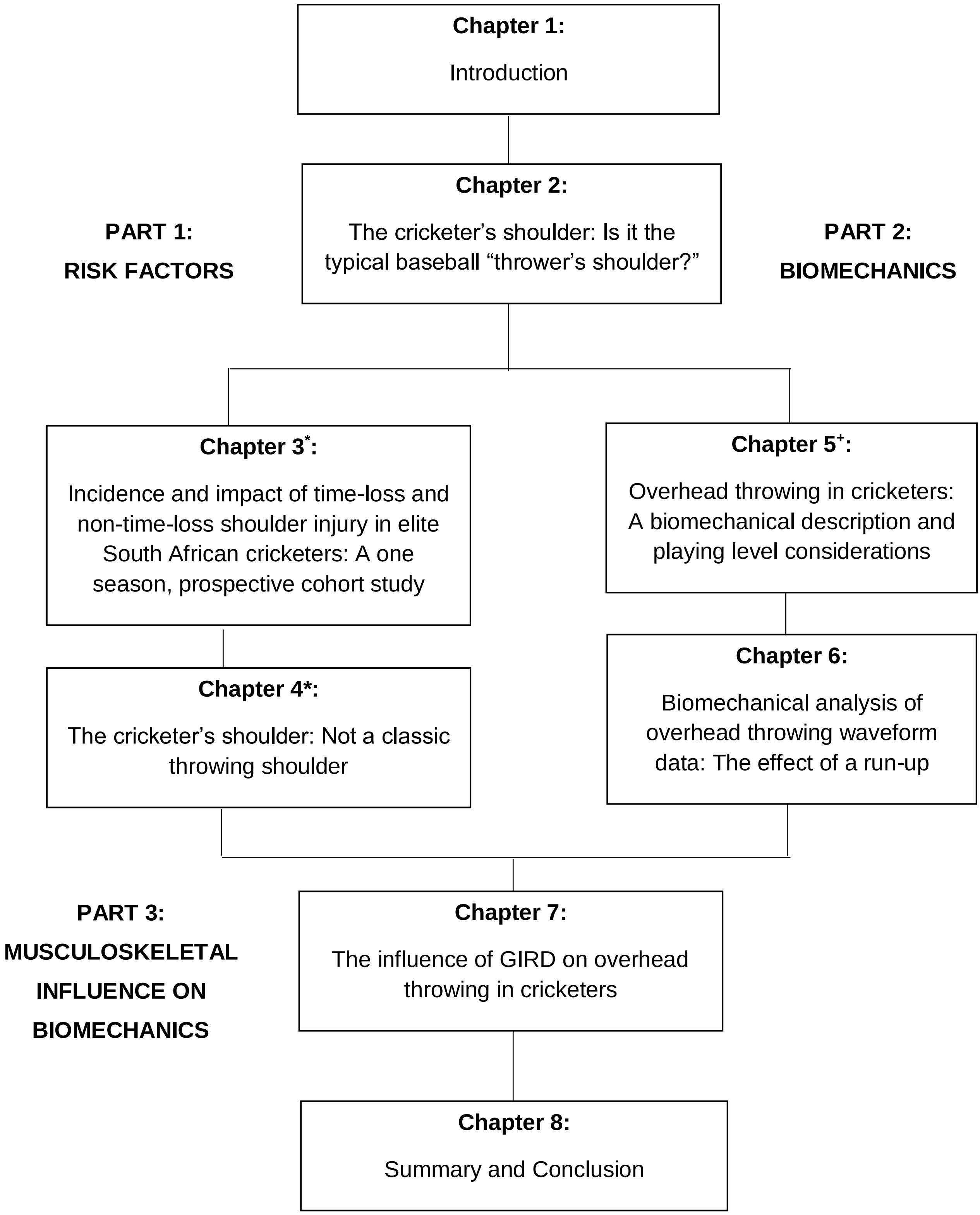


Figure 1.2: Schematic of the thesis structure (Note: *published in peer review journals, +submitted for publication in peer review journals, awaiting feedback).

1.4. AIMS AND OBJECTIVES

In an attempt to understand the impact of cricket on the shoulder joint in elite South African cricketers, the primary aims of this PhD thesis are to:

1. Compare the musculoskeletal profile of the dominant shoulder and overhead throwing biomechanics between cricketers and baseball pitchers currently reported in literature.
2. Determine the incidence of shoulder injuries and musculoskeletal risk factors associated with playing cricket in an elite South African context.
3. Understand the biomechanics of overhead throwing when fielding in cricket through the analysis of broad kinematic and kinetic parameters.
4. Determine the influence of the primary shoulder musculoskeletal adaptation inherent to cricketers, on overhead throwing biomechanics.

In order to achieve the above broad aims, the following specific secondary research aims were addressed (Figure 1.3, 1.4 and 1.5).

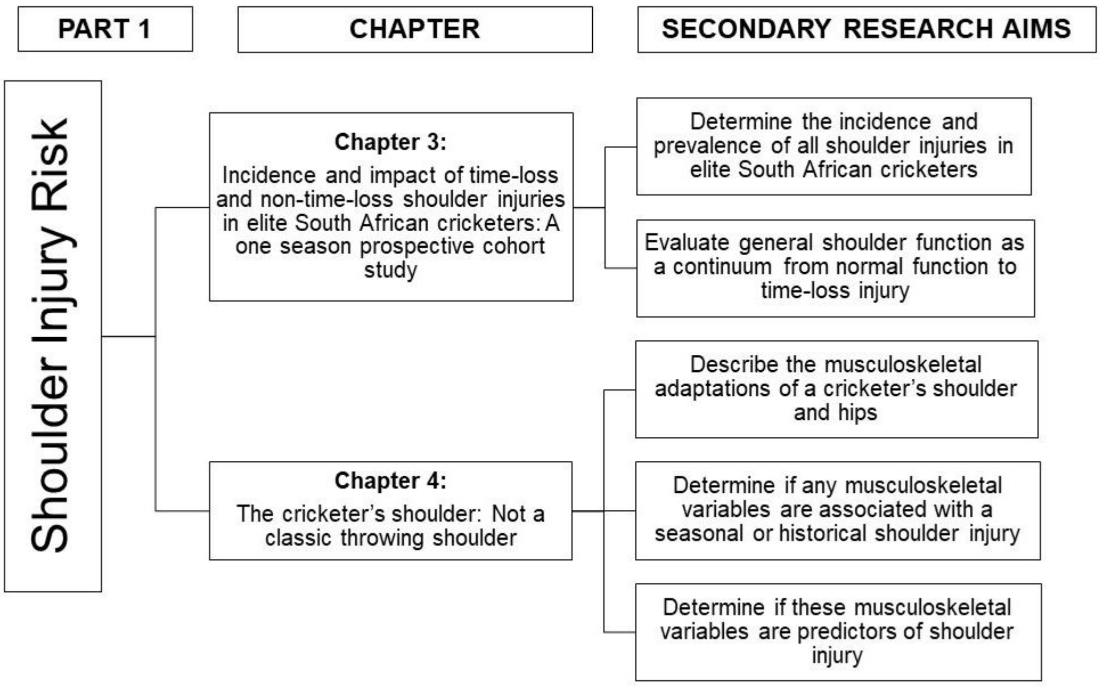


Figure 1.3: Specific secondary research aims and related Chapters conducted in Part 1 - Shoulder injury risk.

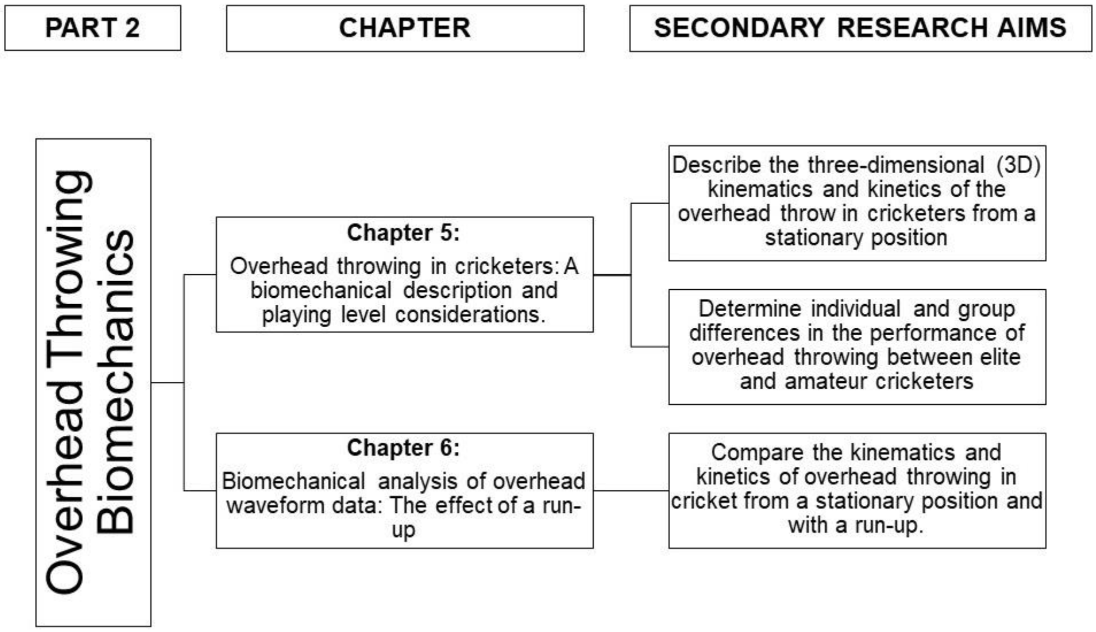


Figure 1.4: Specific secondary research aims and related Chapters conducted in Part 2 - Overhead throwing biomechanics.

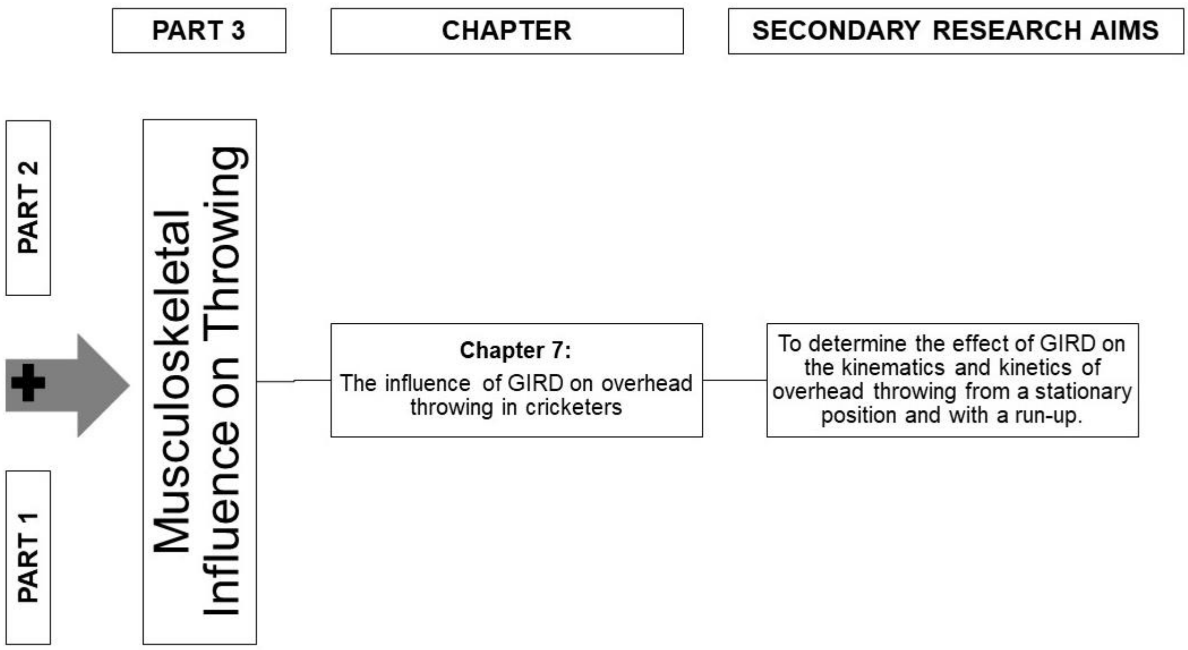


Figure 1.5: Specific secondary research aims and related Chapter conducted in Part 3 - Musculoskeletal influence on throwing.

CHAPTER 2 – REVIEW OF THE LITERATURE:

THE CRICKETER'S SHOULDER: IS IT THE TYPICAL BASEBALL "THROWER'S SHOULDER"?

2.1 ABSTRACT

Throwing is a fundamental movement necessary for many sporting activities, however the demand placed on the shoulder joint complex can often lead to injury. Since the shoulder joint is a complex assemblage of musculoskeletal tissue, achieving performance and preventing injury is based on optimising stability and mobility. The thrower's paradox refers to the delicate balance between shoulder mobility and stability in overhead throwing athletes, to meet the functional demands of a specific sport. Research has consistently shown that these athletes experience a shift in the arc of glenohumeral (GH) rotation, where a gain in GH external rotation (ERG) is associated with a decrease in GH internal rotation (GIRD). This altered pattern of mobility is speculated to occur as a result of soft-tissue and osseous adaptations about the shoulder. Humeral retroversion, upward scapula rotation, posterior capsule inflexibility and strength of the GH external rotators have been implicated in the development of ERG and GIRD. This was found for overhead athletes predominantly in baseball. These adaptations are suggested to allow for greater arm cocking and ball velocity when throwing. Currently, throwing motion analysis studies have likened overhead pitching in baseball, to the overhead throw in cricket. However, several kinetic and kinematic differences in throwing performance have been found between these two sports. Consequentially, it is questionable whether a cricketer does indeed develop these musculoskeletal adaptations as a result of repetitive throwing, typically observed in baseball players. The aim of this review is to present the impact of overhead throwing on the potential musculoskeletal adaptations and associated injury risk, to the shoulder joint in cricketers.

2.2 INTRODUCTION

The shoulder joint complex consists of a series of dynamic articulations which favour mobility over stability. To achieve optimal upper extremity function, a stable base of support and efficient energy transfer from proximal to distal segments is required.[42,43] This is obtained by the dynamic relationship between the bony articulations (static), ligamentous constraints (passive) and muscular (dynamic) forces, primarily between the scapulothoracic and glenohumeral (GH) joints.[42] Any alteration to this relationship may result in shoulder pain or dysfunction.[44-46]

Shoulder pain is thought to be the third most prevalent musculoskeletal injury in the general population.[45,46] Notably, 30-44% of athletes participating in repetitive overhead sports such as baseball,[47,48] tennis,[49,50] swimming,[50,51] waterpolo[52] and volleyball[50,53] develop seasonal shoulder pain. Yet, the sport of cricket which requires overhead motion when bowling and throwing while fielding, yields a seasonal shoulder injury estimation of 23%.[31] Primary subacromial impingement, intrinsic rotator cuff failure, and superior labral lesions have been identified as the most common causes of shoulder pain in throwing athletes specifically.[7,47,48] It is important to note that the seasonal incidence of baseball shoulder injuries has declined since 2007, to a mere 8%.[48] This reduction has occurred as a result of limiting pitch count, minimising throwing load and improving shoulder conditioning,[48] highlighting the necessity to fully understand the biomechanics of overhead pitching/throwing motion and the associated impact on the musculoskeletal profile of the shoulder and injury development.

While the number of studies describing upper limb biomechanics have increased over the last 20 years, the kinematic and kinetic analysis of upper limb motion remains complex and daunting due to the complexity of these joints and modelling restrictions.[54-61] Overhead tasks, such as pitching in baseball or serving in tennis, require the activation of the entire kinetic chain to be performed with precision.[17,20] During tasks such as throwing, the co-ordinated movement of the kinetic chain creates a lag effect, allowing the proximal body segment (e.g. back, shoulder, arm and hand) to accelerate past the distal segment (e.g. legs and pelvis) at a higher velocity.[10] A similar effect is observed when cracking a whip. Consequently, the acceleration of the proximal segments in throwing may result in a humeral velocity >7000°/s,[10,12,18] and ball velocity of approximately 136.8 km/h.[10] In addition, the forces produced by the trunk and legs provide 51-55% of the energy required to throw, which is transferred through the shoulder joint complex.[8] Therefore, it is apparent that the shoulder is exposed to repetitive high loads associated with both high force and velocity from throwing, increasing the potential risk for injury.

Currently, the performance of overhead throwing has been extensively investigated for baseball and specifically during the overhead pitch action.[10,17-19,21] This research has primarily focused on injury prevention and the measurement of mechanical load and stress on the shoulder and elbow joints.[4,10,12,17-19,21,62] In addition, some research has examined the potential kinetic differences of baseball pitching between age groups and playing levels.[63-65] The overhead pitching motion used in baseball is thought to be similar to the overhead throw utilised by cricketers when fielding.[35] A cricket ball is similar in shape and size compared to a baseball, however it is slightly heavier.[35] This may place cricketers on a different force-velocity spectrum when throwing; alternative throwing techniques may be employed, such as the side-arm or sub-marine (under-arm) throw, when throwing during a cricket match situation[36] and this frequently requires the player to throw with a markedly displaced centre of gravity. Currently, little knowledge exists for cricket throwing, with studies providing a two-dimensional (2D) kinematic description from varying approach angels,[1,39] a biomechanical comparison across different throwing techniques[38] and age-related differences in overhead throwing performance.[37]

The current lack of evidence to understand the impact of overhead throwing on shoulder injury risk and performance in cricket, appears to be related to:

I. Undocumented incidence of non-time-loss, in association with time-loss, shoulder injuries in cricket
II. Inadequate description of the musculoskeletal adaptations of the throwing shoulder in cricketers.
III. A limited number of throwing biomechanical studies specific to cricket – the majority of biomechanical studies have been performed on baseball pitching.
IV. Variability in biomechanics – Numerous different recognised styles of throwing in cricket exist, and the individual variability in the execution and performance of these throwing styles have limited the interpretation of studies.
V. Conflicting study design and methodology, such as throwing distances and approaches.
VI. The volumes of data obtained from throwing motion analysis studies are collected and only discrete data is analysed, which may lead to erroneous conclusions.

The purpose of this review is to assess the musculoskeletal adaptations and biomechanical factors associated with shoulder injury risk in overhead throwing. Specifically, a comparison is drawn between the cricketer’s shoulder and baseball pitching shoulder. Further the potential impact of these variables in the development of shoulder pain in cricketers will be explored.

2.3 EPIDEMIOLOGY OF SHOULDER INJURIES IN CRICKET

Numerous injury surveillance studies have been conducted in some of the major cricketing nations across the world, such as England,[29] Australia[28] and South Africa.[6,27,33] These studies have demonstrated a global interest in understanding general cricket injury risk, that highlights bowling,[6,27,28,33] closely followed by fielding[6,27,33] as the activity most frequently associated with injury. Further, the lower limb demonstrates greater susceptibility to injury than the upper limb,[6,27-29,33] resulting in a research emphasis to understand risk factors associated with lower back[66] and hamstring injuries[67] in fast bowlers, specifically. Although approximately 34% of total seasonal injuries pertain to the upper limb,[27,68] with ~40% of the seasonal upper limb injuries sustained while fielding (catching, throwing, diving, collecting the ball)[27,33,69] and ~29% of the fielding injuries, occurring while throwing;[5,6,28] no study has investigated the risk factors associated with upper limb injuries in cricketers.

Initially the prevalence of shoulder pain in cricketers was reported to be five to seven percent of the total injuries sustained per season.[28] However, this injury data only included cricketers who were unable to participate in matches and/or training due to shoulder pain, weakness or instability.[7,31,32] Injury surveillance studies have found that the average time-loss shoulder injury incidence was one injury per 10 000 player hours over a 10-year period[30] or 23-38% per season.[7,31] However the prevalence of shoulder injury resulting in a loss of match time was only 0.8-5.4%.[7,30,31] These studies highlight that despite cricketers experiencing shoulder pain and/or injury reporting a negative impact on performance, specifically throwing, they were still able to continue match play by modifying their fielding position.[7,31] The prevalence of shoulder pain in cricket is comparable to that reported in other overhead sports (30-44%).[47-53] Therefore it is suggested that the prevalence of shoulder pain in cricketers is often under-estimated and it is postulated, based on other research which adapted the definition of shoulder pain/injury to reflect both time-loss and non-time-loss injuries, that 15-36% of cricketers will experience shoulder pain during a season.[7,31,32] The previous under-reporting of shoulder injury in cricketers may explain, in part, the lack of research investigating this injury in cricketers; compared to lower back pain, for example in fast bowlers.[29,33,70]

Currently, several temporal and gross workload variables have been associated with an increased shoulder injury risk in cricket. These variables include timing within a season,[27,71] type of match,[72] level of participation,[72] player speciality,[27,29,33,34,72] throwing load[3] and history of previous shoulder injury[7,27] (Table 2.1). Additional musculoskeletal risk factors associated with the development of shoulder pain in cricketers are discussed in the following section.

Table 2.1: The temporal and gross workload variables associated with the risk of shoulder injury in cricket.

Factor	Associated Risk	Magnitude of Effect on the Shoulder (if known)
Timing in season[27,71]	↑ Pre-Season ↑ End of Season	Unknown
Type of match[72]	↑ Twenty20 matches, followed by one day and then test (five day) matches	Unknown
Level of participation[72]	↑ Elite level	↑ intensity and workload of training and matches
Player speciality[7,27,29,31,33,34,72]	Bowlers	3 to 4 times more susceptible to traumatic time-loss injury
	Batsmen	↑ risk of throwing related shoulder injury due to higher throwing loads during reciprocal batting practice
Throwing workload[3]	>75 throws per week	↑ injury risk by 1.73 times Injured shoulders perform 12.5 throws per day and 40 throws per week more than uninjured cricketers
Injury history[7,27]	Previous shoulder injury	Doubles risk

2.4 MUSCULOSKELETAL RISK FACTORS ASSOCIATED WITH SHOULDER PAIN IN OVERHEAD THROWING ATHLETES

Long-term injury surveillance studies conducted on South African, Australian and English cricketers have reported rotator cuff muscular and/or tendinous injuries as the most common shoulder injury.[27,29,34] Approximately, 25% of the total upper limb injuries (23%) sustained by South African cricketers over 6 years, have been associated with rotator cuff injuries (N = 50) or impingement (N = 42).[6] Bell-Jenje and Gray (2003)[5] reported a similar incidence of shoulder injury over a five year period, in South African academy cricketers. Further, a clinical diagnosis of impingement was made in 75% of the shoulder injuries. In addition, scapula dyskinesis and GIRD, occurred in 67% and 50% of these injuries respectively. These findings support the mild GH instability associated with repetitive overhead throwing hypothesis described by Jobe et al (1989)[73] and modified by Belling Sorensen and Jorgensen (2000).[15] Therefore, the gradual onset of shoulder pain in cricketers may be associated with impingement, secondary to instability.[5,7,15,73]

The aetiology of shoulder pain in cricketers due to secondary shoulder impingement is unclear. Arora et al (2015)[34] proposed a combined mechanism for the development of shoulder pain in cricketers. Repetitive overhead throwing causes the posterior shoulder complex to contract,[13] altering the humeral head and neck position[9,12,13,74,75] with consequential anterior GH laxity[12].

The resultant “pseudolaxity” allows cricketers to obtain a greater external rotation range of motion which places excessive strain on the rotator cuff and may lead to eccentric failure.[12] In addition, the pathological humeral orientation may contribute to scapula dyskinesis.

Shoulder pain occurs due to the mechanical irritation, inflammation and resultant microtrauma of the subacromial bursa or rotator cuff tendons as they are impinged between the humeral head and either the acromial arch or glenoid rim.[14,15,76]

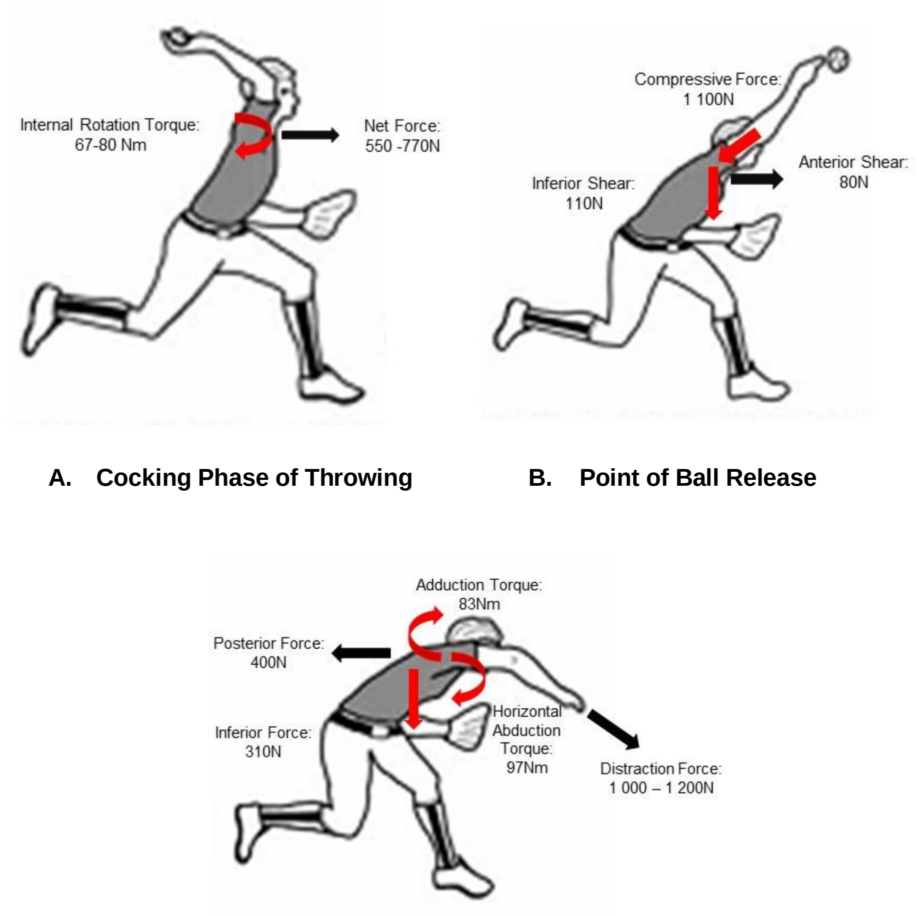
The musculoskeletal factors that may contribute to an increased risk of shoulder impingement in overhead throwing athletes include humeral retroversion,[9,12,74,75,77,78] pain,[12,32,79,80] muscular fatigue,[81-85] scapula dyskinesis with associated muscular imbalances, altered recruitment patterns and poor posture[32,79,80,86-94] and GIRD.[5,13,89,90,94-100] These factors and the associated effect on shoulder pain are summarised in Table 2.2. Notably, much of this information has been described in other overhead sports such as baseball, volleyball and swimming, with very little evidence found in cricket. Further, the influence of overhead throwing biomechanics on the shoulder, biomechanical factors associated with increased risk of shoulder injury and the associated musculoskeletal adaptations of the shoulder joint in response to repetitive overhead throwing, are explored in the following sections.

Table 2.2: A summary of the musculoskeletal factors and associated effects on the development of shoulder pain in overhead athletes.

	Musculoskeletal Variable	Population	Associated Effect
Osseous	*Humeral retroversion*[9]	Baseball[9]	Delays natural humeral anteversion associated with aging[9] and alters arc of GH rotation by ↑ external rotation with an associated ↓ in internal rotation[12,78]
	Circular humeral diaphysis[75]	Cricket[75]	Unknown
Scapula Dyskinesis	*Pain*[12,32,79,80]	Healthy lay individuals[12]	Inhibition of lower trapezius & serratus anterior[12]
		Baseball[79]	Activation of upper trapezius & pectoralis minor[12]
		Cricket[32]	Resultant scapula positioning of protraction[12] downward rotation[32,80] &
		Recreational overhead athletes[80]	posterior tilt[79]
	Muscular fatigue		
	Resisted Shoulder elevation[81]	Healthy lay individuals[81,82,84,85]	↑ scapula motion mid-end shoulder elevation ROM[81]
	Resisted GH external rotation[82,85]	Baseball[83,84]	↑ scapula upward rotation[84,85] & external rotation[84]
	Repetitive overhead throwing[83,84]		↓ scapula upward rotation, external rotation & posterior tilt[82,83]
	Muscle imbalances		
	Overactive upper trapezius[79,89-91]	Healthy lay individuals[91,96,97]	↑ clavicular elevation[79,89-91]
	Inhibition of serratus anterior[87-90]	Shoulder impingement[87,89,90]	↓ scapula posterior tilt[87-90]
	Inhibition of lower trapezius[87,88,90]	Throwing athletes[79,80,86,88]	↓scapula upward rotation[32,80,87-91]
	Inhibition of the rotator cuff musculature[86,90,93,94,101]	Baseball[13,92,98-100]	↑ anterior or superior translation of the humeral head[90]
	Inflexibility of the pectoralis minor[89,90,92]	Cricket[32]	↓humeral external rotation[86,90]
	Posterior shoulder capsule stiffness[5,13,89,90,92,95-99,102]	Swimmers[95]	↑ scapula anterior tilt & internal rotation[89,90,92]
			Contributes to the development of GIRD[5,13,95-100]
	Cervical/Thoracic Posture		
	Slouched posture[95,96]	Healthy lay individuals[96,97]	↓ scapula upward rotation, posterior tilt & GH abduction ROM[96]
		Swimmers[95]	↑ scapula protraction[96]
			↑ GH elevation[95-97]

2.5 THE CURRENT UNDERSTANDING OF THROWING BIOMECHANICS

Various studies investigating throwing technique in baseball, define this motion as a complex skill that requires the sequential co-ordination of pelvic rotation, lumbar extension, trunk and torso rotation, elbow flexion, shoulder external rotation, elbow extension, hip flexion, trunk flexion and shoulder internal rotation.[10,17-21,25,54] An average of 0.145 seconds (s) is the time taken to execute a throw,[10,18] which can be described in six distinct phases including wind-up, stride, cocking, acceleration, deceleration and follow-through.[10,17,18,21,25] When throwing overhead, the upper extremity is subjected to the greatest force during the arm cocking and deceleration phases, as well as at the point of ball release (Figure 2.1).[4,10,12,17-19,21] These three points in the throwing cycle are regarded as critical moments for injury prevention.



A. Cocking Phase of Throwing **B. Point of Ball Release**

C. Deceleration

Figure 2.1: An illustration of the forces and torques experienced by the shoulder at A. Cocking, B. Point of Ball release and C. Deceleration phases of throwing, in baseball pitchers.[4]

2.5.1 Cocking Phase of Throwing

Maximum shoulder external rotation (MER), equivalent to 165-180°, occurs between 80-100° of shoulder abduction[18] during the cocking phase of throwing. This position is regarded as the first critical moment in the throwing motion, for two reasons. Firstly, the subacromial space needs to be maintained at MER, in order to minimise the potential risk for impingement. This is achieved by positioning the scapula in full retraction, upward rotation and posterior tilt.[17,18] Secondly, the elbow and hand lag behind the trunk and torso during forward rotation, placing significant strain on the anterior shoulder joint.[4,10,17,18,21] A study conducted on baseball pitchers, demonstrated that near MER, the shoulder may be subject to a net force between 550-770 N and may experience 67-80 Nm of internal rotation torque and up to 100 Nm of horizontal adduction torque.[4] These loads are countered and balanced by the infraspinatus and teres minor muscles, as well as the long head of biceps brachii which provide shoulder stability by reducing anterior translation of the humeral head on the glenoid.[18,103,104] Importantly, an increased maximum external rotation has been shown to positively influence ball velocity when throwing.[10,11]

2.5.2 Point of Ball Release

The point of ball release is regarded as the second critical moment in the throwing motion, as the compressive forces on the pitching shoulder have been shown to progressively increase from approximately half body weight (480N) to almost full body weight (1100N) at ball release.[4] In addition, anterior shear diminishes to 80N and a mild inferior shear of 110N develops.[4] The dynamic compression functions as a stabilising mechanism for the GH joint at ball release and is thought to be provided by the concentric contraction of the rotator cuff musculature, which is enhanced by the eccentric action of the biceps brachii.[10] It is vitally important that the throwing arm maintains a position of greater than or equal to 90° shoulder abduction at ball release, in order to optimise strength, enhance ball velocity and reduce the risk for shoulder impingement.[19]

2.5.3 Deceleration Phase of Throwing

The final critical moment in throwing occurs during the deceleration phase, where a pitching shoulder is subjected to a distraction force equivalent to 108% of body weight (1000-1200N).[4] In order to decelerate the throwing arm and resist horizontal adduction, a posteriorly directed force of approximately 400N is required.[4] It is proposed that this is provided by the eccentric action of the posterior shoulder musculature, including the teres minor, infraspinatus and posterior deltoid.[18] In addition, anterior humeral translation is limited by the posterior shoulder capsule and glenohumeral (GH) ligaments, which produce a horizontal abduction torque of approximately 97Nm.[4]

Lastly, the dynamic and passive stabilisers around the GH joint resist abduction and superior humeral head translation by producing an adduction torque of approximately 83Nm and inferiorly directed force of approximately 310N, respectively.[4]

It is important to note that kinematic and kinetic differences in baseball pitching have been identified between age groups and playing levels.[63-65] Elbow flexion which significantly increases with age, is the only kinematic difference which has been identified between age groups.[63] However, a significantly lower shoulder rotation torque and delayed trunk rotation occurs when comparing the highest to lowest level of play.[65] Further, injury risk is directly proportional to joint torque which increases as the level of play becomes more competitive.[63]

The large forces exerted on the shoulder during throwing pose a risk for injury, by nature of their magnitude. A summary of the forces, the musculoskeletal control and injury implications experienced at the critical points in the overhead throwing cycle is presented in Table 2.3. Further biomechanical variables (Table 2.4) have been identified in throwing athletes. Their relationship with regards to causation of shoulder injury may not always be clear but the impact of a number of biomechanical variables along the entire kinetic chain on the load experienced by the shoulder is clear.

Table 2.3: The forces, musculoskeletal control and associated injury implications at the critical points in the overhead throwing cycle of baseball pitchers.

Forces	Reference Data[4]	Musculoskeletal Control	Injury Implications
Maximum External Rotation			
Compression	480 ± 130	Rotator cuff complex (specifically supraspinatus) and deltoid[105-107]	*Less compression, increases superior and anterior shear, causing:*
Superior	250 ± 80	Humeral head depressors, specifically mm subscapularis and long head of biceps brachii[42,108] Shoulder capsule and labrum[10]	Less GH stability[18,103,104] ↑ strain on anterior shoulder[10,18] ↑ risk for impingement[18] and associated rotator cuff strains/tendinopathies[4,18]
Anterior	380 ± 90	Concentric mm infraspinatus, teres minor and long head of biceps brachii[18,103,104]. Eccentric contraction of mm subscapularis, pectoralis major, anterior deltoid and latissimus dorsi[10] Shoulder capsule and labrum[10]	
Ball Release			
Compression	1 090 ± 110	Concentric rotator cuff and eccentric biceps brachii[10]	*Less compression, increases superior and posterior shear, causing:*
Superior	240 ± 80		Less dynamic GH stability[10]
Anterior	80 ± 180		↑ risk for ligamentous and labral injuries[4]
Maximum Internal Rotation			
Distraction	1 100 ± 100	Eccentric contraction of teres minor and major, infraspinatus, posterior deltoid, latissimus dorsi[10,18] and posterior shoulder capsule[4,18]	*Increased distraction, increases inferior and posterior shear, causing:*
Inferior	310 ± 80		Rotator cuff strains and/or tendinopathy[4]
Posterior	400 ± 90		Labral injuries[4]

Table 2.4: Additional biomechanical and neuromuscular risk factors associated with shoulder injuries in overhead throwing athletes.

Biomechanical Variable	Phase of Throwing	Effect on Throwing Technique	Effect on Shoulder	Associated Injury (if known)
Reduced dominant hip abduction strength[18,20,22]	Wind-up	Unstable base of support	Increased load to maintain throwing velocity & accuracy	Posterior superior labral tears (49% of cases)
Dominant hip internal rotation deficit[17,18,20,21]	Stride	Early forward rotation ("opening up") of pelvis	Increased load and forces	Unknown
Non-dominant hip external rotation deficit[17,18,20,21]	Stride	Open foot placement in excess of 15° ± 10° (measured from a line bisecting the dominant ankle and target)[25], increases the load on the abdominals, anterior shoulder and valgus force at the elbow	Increased anterior shoulder force by 3 N for every 1 cm of foot "opening"[25]	Unknown
Early glenohumeral external rotation[17,18,25]	Early Cocking phase	Early trunk rotation towards the target Placing hand on side of, or under ball	Increased anterior shoulder force by 1.3 N for every 1° in excess of 53° ± 26° GH external rotation at the point of stride foot contact	Anterior instability of laxity
Delayed glenohumeral external rotation during stride[17,18,25]	Cocking	Increased load on shoulder	Increases longitudinal compressive force of humerus by 1.5 N for every 1° in excess of 53° ± 26° GH external rotation	Glenohumeral labral injuries
Glenohumeral internal rotation deficit (GIRD)[8,17-20]	Cocking	Increased valgus stress on the elbow	Increased humeral head anterior or superior translation	GIRD greater than 18°-20°, increases risk for injury for superior labral anterior to posterior tears, rotator cuff impingements and strains
Reduced elbow flexion[17,18,23-25]	Cocking & ball release	Increased load on shoulder	Increases longitudinal distraction forces	Glenohumeral labral or rotator cuff injuries
Lumbar hyperlordosis[17,20]	Acceleration	Throwing arm positioned behind the body in greater shoulder abduction and external rotation	Increases compression through shoulder	Unknown

2.6 THROWING: A BASEBALL AND CRICKET COMPARISON

As previously mentioned, the overhead pitching motion used in baseball, is often likened to the overhead throw utilised by cricketers when fielding.[35] However significant differences in throwing performance and biomechanics exist between these two sports. These variables are compared and the clinical implication highlighted, in Table 2.5.

Table 2.5: A comparison of throwing performance and biomechanics between baseball pitchers and cricket players.

Variable	Baseball (Pitching)	Cricket (Overhead Throwing)	Potential Clinical/Biomechanical Implication
Ball Weight[35] (g)	142	156	Greater force is required to throw a heavier ball at high velocity
Stride Length [37] (% of body height)	77.7	65.4	Stride length impacts ball velocity. A shorter stride results in a slower ball.
Elbow flexion during stride phase of throwing[37,109,110] (°)	94-101° when pitching	69.9° when throwing over 73.2 metres	Difference in vertical release trajectory of ball, indicates that cricketers have a 'preparatory arc' rather than a definitive withdraw of the arm prior to acceleration phase of throwing
Maximum Throwing Speed[1,109,111] (m/s)	30.3 ± 0.5 m.s^{-1}	27.9 ± 0.5 m.s^{-1}	Baseball players have significantly higher throwing speed ($p < 0.01$), than cricketers
Throwing Accuracy[111] (best achieved at 80% speed)	24.2 ± 0.6 m.s^{-1}	22.3 ± 0.5 m.s^{-1}	Baseball players have significantly greater accuracy ($p < 0.05$), than cricketers

These differences may be the result of the respective demands of each sport. Pitching is performed from a static position and requires the leisurely yet definitive withdrawal of the arm. In addition, the ball is transferred from the non-dominant "gloved" hand to the throwing hand which encourages baseball pitchers to assume a side-on body position prior to throwing. Conversely, fielding in cricket requires a rapid transition of the whole body from ball pick-up to throw. This dynamic movement of a cricketer may result in a "preparatory arc" of the upper limb prior to the acceleration phase of throwing. Further, cricketers may assume a more open body position to execute a throw, as they tend to use their dominant hand to field a ball.[1,35-37,109-111]

2.7 THROWING STYLES IN CRICKET

The overhead throw is preferred by cricketers, when a throw of maximum or near maximum velocity is required.[36] However, when attempting to reduce the number of runs scored by the opposition or dismiss a batsman via a run-out, the fielder in cricket may compromise their overall throwing technique in favour of a quick ball release. The alternative throwing techniques including the side-arm or sub-marine (under-arm) throw may thus be required.[36] The side-arm and sub-marine throws have similar phases to the overhead throw, but slight variations in biomechanics, and are classified according to the degree of shoulder elevation, where overhead throwing shoulder elevation is > 100°, side-arm throwing shoulder elevation is between 90-100° and sub-marine throwing shoulder elevation is <75°.[25]

2.7.1 Overhead Throwing in Cricket

Presently, limited biomechanical evidence for the description of overhead throwing performed by cricketers when fielding, exists.[1,37,39] Two studies have assessed overhead throwing technique over 20 and 40 metres, with straight and 45° angled approaches to the stumps, respectively.[1,39] These studies used 2D kinematic analysis from back foot strike to ball release in order to describe the preparatory arc to ball release phases of overhead throwing in cricket. Differences in stride length, degree of elbow flexion, maximum shoulder external rotation, angle of ball release and ball velocity where found between maximum velocity throws from 20-m and sub-maximal velocity throws performed from 40-m. These findings highlight a slight difference in the sequential co-ordination of throwing when performed over 40-m, as the maximum shoulder velocity occurs at or before that of the hip. This implies that a speed-accuracy trade-off occurs when throwing from 40-m, specifically. However, these studies were limited in sample size and neglected to describe overhead throwing from BR to arm deceleration. More definitive research using larger sample sizes, different playing levels and 3D motion analysis will provide greater insight into both throwing performance and the biomechanical influences relevant to injury. Further, the kinematic characteristics from BR to arm deceleration and kinetic load subject to the shoulder throughout the overhead throwing cycle in cricket, is unknown.

2.7.2 Comparison of Throwing Techniques in Cricket

A paucity of knowledge exists for the comparison of biomechanical variables across different throwing techniques, with only a single study conducted in cricket.[38] This study assessed 2D throwing techniques over a 30-m distance with different approach angles, including 45°, 90° and 180° relative to the cricket stumps and only assessed the wind-up, cocking and acceleration phases. Differences in angular velocity for the cocking to acceleration phase of the wrist, elbow, shoulder and knee joints were found between throwing techniques, at different approach angles.

The exact differences in angular velocity cannot be discussed due to the lack of absolute values reported in this study. However, these findings highlight the large variability in upper limb range of motion; and difference in movement pattern required, when performing different throwing techniques at different approach angles. Conversely, no differences were found for the hip and ankle joints indicating that the overall contribution of these two joints to the throwing motion remains relatively constant irrespective of the throwing technique selected. In addition, overhead throwing produced the greatest ball velocity, followed by the side-arm and sub-marine techniques. A similar trend for accuracy was noted between throwing techniques, with the best approach angle found to be 180° relative to the stumps.

Failure to fully describe the phases of throwing used, the direction of joint movement and the allowance for individual variation between throwing techniques limits further interpretation of these findings. Further, while it is known that medial elbow forces and anterior shoulder force increase with the performance of the side-arm and sub-marine pitch respectively,[112] this study neglected to investigate the possible differences in joint kinetics of various cricket throwing techniques. Therefore, the overall contribution of each body segment to throwing motion; as well as the forces and torques experienced by each joint, are unknown. What is apparent is that the force and velocity experienced by the shoulder when performing an overhead throw in cricket is not well understood, although it possibly is pivotal in injury risk, and requires further investigation.

2.8 THE THROWING SHOULDER: MUSCULOSKELETAL ADAPTATIONS

Repetitive overhead throwing, in sports such as baseball, handball and volleyball, has been associated with a variety of shoulder specific musculoskeletal adaptations, including but not limited to:

I. Altered humeral retroversion angle[9,74,77]
II. Modified scapula kinematics[12,32,80,86,113]
III. Glenohumeral rotational laxity[7,8,13,15,73,76,114,115]
IV. Differences in acromiohumeral distance[116-120]
V. Glenohumeral rotational strength

These factors often contribute to changing the arc of motion for overhead athletes, as a gain in GH external rotation ROM (ERG) occurs with a similar deficit in GH internal rotation ROM (GIRD).[12,78] This allows overhead athletes to achieve the “thrower’s paradox”, which is a delicate balance between shoulder stability and mobility, in order to realise optimal throwing performance.[40] Currently, the potential contribution of these musculoskeletal changes to throwing performance and the development of shoulder pain and injury in cricketers, is unknown and requires further exploration.

2.8.1 Humeral Retroversion

Humeral retroversion is the angle created between the vector bisecting the longitudinal axis of the humeral head and neck; and that along the transverse axis of the humeral condyles.[12,77] Edelson (1999)[77] measured 336 dry humeri specimens, across varying ages and a variety of ethnic groups. Humeral retroversion was shown to gradually reduce during growth and development, primarily between the ages of 12 and 16, when the proximal humeral epiphysis is still open.[9,74,78] Retroversion reduces from a mean foetal measurement of 78° to a mean adult measurement of 30°.[77] In addition, the dominant arm demonstrates a slightly greater humeral retroversion angle than the non-dominant arm.[77]

These findings are suggested to occur as a result of the increased stress and workload applied to the dominant arm.[9,74,77]. Throwing athletes have been reported to demonstrate similar humeral retroversion differences between the dominant and non-dominant shoulders.[74] However, the degree of humeral retroversion achieved by throwing athletes (specifically baseball players) in adulthood is reported to be approximately 45°.[9] This is a substantially greater angle compared to the mean adult measurement of 30° observed by Edelson (1999).[77] Consequently, repetitive throwing is thought to delay the physiological de-rotation process of the humeral head during normal growth.[9,74] This osseous adaptation may be responsible for GH rotational asymmetries, ERG and GIRD; and may potentially reduce the excessive strain on the anterior capsuloligamentous structures during the cocking phase of throwing.[78]

Currently very little evidence exists to support the presence of humeral adaptations in cricketers. A single study has demonstrated that cricketers have a greater circular humeral diaphysis compared to inactive individuals.[75] This is thought to occur in response to the torsional loading associated with throwing, thereby allowing the humerus to resist shear forces. In addition, cricketers also have greater rigidity of the dominant arm humerus when compared to their non-dominant arm and inactive individuals,[75] this may be an adaptation to the mechanical loading of the upper limb in this sport. However, it is questionable as to whether cricketers will achieve the reduction in humeral retroversion noted in baseball. As cricket is a multi-disciplinary sport, requiring specific skills training in the areas of batting, bowling and fielding, it is possible that young developing cricketer's do not adequately load the shoulder through throwing to achieve this adaptation. Further investigation is required to determine this, especially at younger and lower levels of participation.

2.8.2 Modified Scapula Kinematics

Modified or altered scapula kinematics is frequently observed in athletes participating in overhead sports, such as baseball, tennis and volleyball.[12,32,78,80,86,113] These athletes demonstrate greater scapula upward rotation, internal rotation and retraction during overhead elevation of the dominant arm, when compared to the non-dominant arm and the arms of inactive individuals.[86,113] This modification in scapula movement occurs during the cocking phase of throwing specifically and occurs as a result of the load applied to the upper limb during overhead sports.[17,18,86] There is at present no evidence for modified scapula kinematics in cricketers.

Pathological scapula positioning of downward rotation, protraction and anterior tilt, is reported in overhead athletes with shoulder pain.[12,32,79,80] Green et al (2014)[32] demonstrated that cricketers experiencing shoulder pain exhibit greater downward scapula rotation at 90° GH elevation, when compared to those players without shoulder pain. In addition, shoulder pain is known to inhibit the serratus anterior[87-90] and lower trapezius muscles,[87,88,90] while an increased activation of the upper trapezius and pectoralis minor muscles[12] has been observed. The resultant scapular instability has been shown to occur in 68% of rotator cuff injuries, and 100% of GH injuries.[87,88]

The unknown presence of increased humeral retroversion and modification of scapula positioning in cricketers, brings about the question as to how these athletes may achieve maximum external rotation. It is plausible that Jobe's theory (1997)[121] of anterior capsuloligamentous hyperlaxity, concomitant humeral head translation and associated increase in passive GH external rotation ROM, may occur. Sethi et al[122] assessed anterior-posterior humeral translation and ERG in baseball players. It was noted that pitchers had greater translation and ERG in their throwing shoulder, compared to their non-throwing shoulder. Further, an asymmetry of >3mm between throwing and non-throwing shoulders was found in pitchers, compared to positional players. Secondly, MER may be achieved by the posterior shoulder capsule adapting to allow for greater posterior humeral translation in the cocking position. This phenomenon was illustrated by Borsa et al (2005)[123] in a study correlating range of motion and glenohumeral translation in professional baseball pitchers, with an average of 5.9 mm of posterior humeral translation in the dominant arm when positioned in the cocking phase of throwing.[123] This measurement is on the upper spectrum of the reported normal posterior humeral translation of one to five millimetres.[78] Although shoulder pain is prevalent amongst cricketers, little is known about the anatomical adaptations of the shoulder to throwing in cricket. Further, the potential relationship between these adaptations and the aetiology of shoulder pain in cricket, is unknown.

Therefore, future research concerning the development of acquired anterior hypermobility and ERG, as well as potential shoulder injury risk, in cricketers is required.

2.8.3 Glenohumeral Rotational Laxity

The development of glenohumeral rotational laxity during overhead throwing, is thought to occur during the late cocking and deceleration phases specifically.[12] The ERG achieved during the cocking phase may overload the posterior shoulder complex, as greater concentric activity is required.[12,78,123] Additionally, numerous studies have shown that the posterior shoulder complex is subjected to frequent eccentric loads during the deceleration phase of throwing[76,114,115] and may become stiff or contracted.[12,13]

Tightness of the posterior shoulder in baseball players has been found to demonstrate a moderate to good linear relationship with scapula protraction and anterior tilt;[92] and GH horizontal adduction and internal rotation ROM.[13,98-100] This linear relationship is highlighted in the deceleration and follow-through phases of throwing, where a large range of GH horizontal adduction is required.[17,18] Posterior shoulder tightness restricts the range of available GH horizontal adduction which may result in overhead thrower's acquiring an increase in scapula protraction to complete the throwing action.[78] Similarly, a concomitant reduction in GH internal rotation ROM is thought to occur, as this motion is inter-related with GH horizontal adduction in a ratio of 1 cm:4-5° (i.e.: a 1 cm reduction in GH horizontal adduction, results in a concomitant 4-5° loss in GH internal rotation).[124]

Giles and Musa (2008)[7] have shown that junior cricketers who regularly participated in overhead activity demonstrated the GH rotational asymmetries of ERG and GIRD. An average increase in GH external rotational ROM of 8.6° and a concomitant decrease in GH internal rotational ROM of 7.9°, is reported.[7] In addition, these changes in GH rotation are greater in the dominant shoulder than the non-dominant shoulder.[7] Similarly, recurrent bowling has been associated with similar changes in the arc of GH rotation.[8,125] However, it is questionable as to whether these changes occurred due to bowling load as all bowlers are required to field.

Borsa et al (2008)[78] argue that the observed shift in GH rotational arc prevalent in overhead throwing athletes, is largely due to the attainment of humeral retroversion and that shoulder pathology occurs as a result of the super-imposition of capsuloligamentous changes on this osseous change. To date, GH rotational laxity is the only known adaptation to repetitive throwing demonstrated by cricketers. As such, Borsa et. al's (2008)[78] theory is currently not applicable to this subset of overhead throwing athletes.

2.8.4 Differences in Acromiohumeral Distance

Acromiohumeral distance is an ultrasonographic measure of the subacromial space from the inferolateral edge of the anterior acromion to the humeral head.[126] Maintenance of the subacromial space in overhead activity is provided by the synergistic contraction of the serratus anterior and lower trapezius muscles which allow for scapula upward rotation and posterior tilt,[87,88,90,127] as well as optimal activity in the rotator cuff muscular complex to control superior humeral head translation.[90] Muscular imbalances between either the scapula stabilisers or the GH internal and external rotators, may compromise the AHD resulting in an external or subacromial impingement.[14,15,76] Research has identified that a larger AHD measurement His associated with good GHER strength and a high GHER:GHIR ratio in volleyball players.[116] Conversely, a smaller AHD measurement is associated with GIRD >15° in overhead athletes.[117,118]

Further, conflicting evidence regarding potential differences in AHD measurements between the dominant and non-dominant shoulders of asymptomatic baseball[119,120] and volleyball[116,118] players exists. Baseball players appear to have bilateral shoulder symmetry in AHD and SsT thickness,[119,120] whereas volleyball players demonstrate larger AHD measurements with an increased SsT thickness of the dominant, compared to non-dominant, shoulders.[116] These discrepancies in research may be attributed to the fact that the baseball players participate in bilateral shoulder training and conditioning, whereas volleyball players tend to load the dominant shoulder more during training. Currently, the AHD has yet to be measured in cricketers. However, it is thought that cricketers may display similar AHD and SsT measurements to those found in volleyball.[93,128] Consequently, a reduction in the GHER:GHIR strength ratio is expected, increasing the potential risk for shoulder injury over time.[93,116] Research has found that the development of throwing-related shoulder pain is associated with a loss of shoulder strength, specifically in the supraspinatus and middle trapezius muscles.[93,94] This may further be attenuated by GIRD and a reduction in the total arc of GH rotation >5°.[94] While GIRD[5] and greater GHIR strength[125] have been noted in cricketers with shoulder injury, no differences in GHER strength have been observed. Further, the cricketer's GH rotational strength ratio has yet to be described and requires further investigation.

2.9 CONCLUSION

It appears from the current literature that a cricketer's shoulder may not fully exhibit the "thrower's paradox" often observed in baseball players. Research has identified a circular humeral diaphysis and GH rotational laxity in cricketers, rather than the extreme shift in arc of GH rotation and modified scapula positioning observed in baseball. Subsequently, the lack of musculoskeletal adaptations currently reported suggest that the pathological process for shoulder pain in cricketers, is gradual. In addition, the potential influence of the presence of these musculoskeletal adaptations on the performance of overhead throwing in cricket is unknown. Further research in the assessment of throwing biomechanics; and the musculoskeletal presentation of the shoulder in cricket players, is required to better understand the presence of the classic "throwing" shoulder in cricketers.

PART 1

CHAPTER 3 – INCIDENCE AND IMPACT OF TIME-LOSS AND NON-TIME-LOSS SHOULDER INJURY IN ELITE SOUTH AFRICAN CRICKETERS: A ONE-SEASON, PROSPECTIVE COHORT STUDY

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For the purposes of this thesis, figures and tables as well as their captions have been placed in the appropriate places within the text of the article and general formatting is aligned with the requirements of the Doctoral Degrees Board, University of Cape Town.

A copy of the questionnaire utilised in this Chapter can be found in Appendix I.

3.1 ABSTRACT

Objectives: To determine the incidence, prevalence and impact of shoulder injury in elite South African cricketers.

Design: Prospective longitudinal cohort study

Methods: One hundred and six senior national or franchise cricketers completed a pre-season Kerlan-Jobe Orthopaedic Clinic shoulder and elbow (KJOC) score. All injuries sustained during the 2016/2017 season were captured on an injury reporting system. Injuries were verified by the respective squad physiotherapist at the end of the season and post-season KJOC score was obtained from all the players.

Results: Eighteen percent (95% CI: 11-25%) of cricketers sustained a shoulder injury, at a rate of 0.19 injuries per player per year. Annual injury prevalence was 1.1%. Shoulder injury occurred primarily while throwing (58%). Fielding performance was maintained by adapting throwing technique (58%) or fielding position (21%). Thirty-two percent of shoulder injuries resulted in time lost to matches and/or training. A history of shoulder injury increased the risk of sustaining another injury by 1.91 times (95% CI: 1.73-2.15). Irrespective of injury, elite South African Cricketers demonstrated consistently low pre- (78.5 ± 15.6) and post-season (81.2 ± 17.1) KJOC scores. Pre-season KJOC scores were significantly lower (r^2=0.106, p=0.001) in those cricketers with a history of previous shoulder injury. Cricketers who sustained a seasonal shoulder injury had significantly lower (r^2=0.112, p<0.001) post-season KJOC scores, indicating persistent shoulder pain or dysfunction.

Conclusion: This is the first study to report both time-loss and non-time-loss shoulder injury in elite South African cricketers. All non-time-loss shoulder injuries compromised primary skill, while some resulted in changes to throwing technique and fielding position. Thus shoulder injury, whether it results in time loss or not, potentially impacts performance during a match.

Keywords: Epidemiology, incidence, prevalence, shoulder, cricket

3.2 INTRODUCTION

Shoulder injuries have previously been reported to account for 5-7% of all injuries amongst elite cricketers.[27-30] These injury surveillance studies defined an injury as, a musculoskeletal condition that prevented a player from being selected for match participation or inhibited a player from further participation in a match.[129] The use of this "match time-loss" definition may overlook 70-92% of injuries.[130] In fact 69-85% of cricketers with shoulder pain/injury are able to continue training and match play, by fielding in a different position.[7,31,32]

Since the "match-time-loss" injury definition is not suitable for shoulder injuries, recent injury surveillance studies in cricket have either adapted the definition of shoulder injury/pain used in self-report questionnaires,[7,31] or used a battery of shoulder questionnaires to assess function (Kerlan-Jobe Orthopaedic Clinical shoulder and elbow (KJOC) score) and instability (Melbourne Instability Shoulder Score and the Western Ontario Shoulder Instability Index).[32] With the use of this alternate approach (i.e.: inclusion of non-time-loss in the definition of injury), shoulder injuries have been found to account for between 15% and 36% of all injuries in elite junior Australian and English cricketers, respectively; and 23-36% of all injuries in elite senior English cricketers.[7,31,32]

The most common shoulder injury reported in literature for cricketers, pertain to the rotator cuff musculature and/or tendons[27-30,34] and is thought to be associated with an impingement mechanism.[5,6] Overhead throwing when fielding is considered the most provocative activity associated with shoulder injury in cricketers.[6,27-29,31,33] Bowlers have a tendency to be positioned in the outfield during matches and are thus required to throw over large distances placing greater force on the shoulder joint, increasing their susceptibility to shoulder injury.[3,31,32,34] Other factors which are known to contribute to the development of cricket related shoulder injuries include time of season (early season, due to lack of conditioning; and end of the season, due to fatigue),[27,71] shorter formats of the game (T20 > ODI > Test),[72] progression of level of play and competition (elite > amateur > youth > junior)[72] and history of previous shoulder injury.[7,27]

The investigation of non-time loss shoulder injuries in cricketers is essential to determine the effect on performance and associated development of musculoskeletal imbalances which may alter movement sequencing patterns, potentially resulting in more serious "time-loss injuries". Therefore, the aim of this study was to determine the incidence and prevalence of all shoulder injuries in elite South African cricketers irrespective of time lost to match and training participation. In addition, general shoulder function was evaluated as part of a continuum from normal shoulder function to time-loss injury.

3.3 METHODS

All male cricketers representing a South African franchise or senior national team underwent an annual pre-season musculoskeletal screening. For the 2016/2017 season, all players were invited to participate in this study. Four players were unavailable to participate in the study as they were currently playing abroad. A further 19 players were also unavailable as they came from a franchise whose medical management were unavailable to co-ordinate testing. The study was approved by the Human Research Ethics Committee, University of Cape Town (HREC: 364/2016). All participants provided written informed consent prior to the commencement of the study.

Participants completed a questionnaire to obtain demographic data; training, competition and injury history, as well as the KJOC score prior to the commencement of their annual pre-season musculoskeletal screening. Training data included the weekly frequency and number of hours spent performing the cricket disciplines of batting, bowling and fielding; as well as performing cardiovascular fitness and strength based exercises. Competition data was obtained by players indicating selection availability per match format (i.e. multiple-day, one-day or T20 matches) based on the season fixtures. Injury history included all injuries sustained by the player over the last 5 years. This information was entered into a database at the original time of injury by the team medical staff (physician or physiotherapist) and subsequently extracted for the purposes of this study. Lastly, the KJOC score is a shoulder function questionnaire, specific to overhead athletes.[131] It comprises 10 questions, divided into three sections that include function and athletic performance, symptoms related to the upper limb and interpersonal relationships related to performance, to create a total of 100-points. Each question is measured using a 10cm visual analogue scale, where 0 = lowest level of function/performance and greatest severity of the symptom assessed and 10 = highest level of function/performance and lowest possible severity of symptom assessed. A score <90% indicates the absence of full shoulder function[132] and is thus considered to be clinically relevant. Alberta et al (2010)[131] found the KJOC Score to be both a reliable (ICC = 0.88) and valid (r = 0.84-0.86) measure of shoulder and elbow function in intercollegiate and professional overhead athletes.

Completion of these two questionnaires (demographics and KJOC) occurred over a two-week period in September, which is the start of the domestic cricket season. As the National team play all year round and do not have a specific pre-season, testing was conducted at a training camp which coincided with the start of the domestic season.

The National and franchise cricketers were then followed for a period of six months, from October to March, which constituted the 2016/2017 domestic cricket season, and all injury data were collected for this period.

Shoulder function was selected to determine the required sample size,[32] as functional ability is the primary outcome measure of this study. The smallest meaningful difference (SMD) and minimal detectable change (MDC) for the KJOC score have yet to be determined. However, the KJOC score was validated against the DASH questionnaire[131] which has an SMD of 16.3 and MDC of 12.4.[133] These values were thought appropriate to determine the required sample size for shoulder function. With statistical significance accepted as $p < 0.05$, 18 participants will provide 80% statistical power for shoulder function. Note the national squad of 15 cricketers yields 67% statistical power for shoulder function.

All injuries sustained by participants in the 2016/2017 cricket season were recorded prospectively by the respective squad medical personnel (medical doctors or physiotherapist) and loaded onto an online injury reporting system. For the purposes of this study, shoulder injury was defined as a “medical attention” injury as proposed in the updated international consensus statement on injury surveillance in cricket by Orchard et al (2016).[134] Therefore, any shoulder-related condition sustained during competition and/or training that required medical attention, irrespective of time lost to training and/or competition was noted as a shoulder injury. In addition, clinical diagnosis of injuries followed the International Statistical Classification of Disease and Related Health Problems (ICD) list, produced by the World Health Organisation (WHO).[135] Note that where a cricketer sustains an identical injury to the same musculoskeletal structure, without further/different pathology, during the period of surveillance in this study, shoulder “injury recurrence” rather than a new injury, is recorded. All injury data was corroborated at the conclusion of the 2016/2017 cricket season with each respective squad physiotherapist. No changes to the recorded electronic data were required. All participants repeated the KJOC score at the end of the season.

Shoulder injury incidence and prevalence for the 2016/2017 South African Cricket season was calculated using the guidelines recommended by Orchard et al (2016),[134] which considers a standard squad as 100 players and a cricket season as 365 calendar days. Annual injury incidence was determined as: *total injuries x (standard squad size x standard cricket season)/(actual squad size x number of match days)*. Match injury incidence was determined as: *1000 x (total injuries/total match days)*. Annual injury incidence was reported in the unit of injury per player per year, while match incidence was reported as number of injuries per 1000 player hours.

Annual injury prevalence was determined as: *100 x (total missed cricket days)/(actual squad size x standard cricket season)*. Match prevalence was determined as: *100 x (number of missed cricket matches)/(total number of matches x actual squad size)*. Both annual and match prevalence were expressed as a percentage. Orchard et al (2016)[134] describe annual injury prevalence as: *"The percentage of players unavailable on the basis of general time-loss status taking into account daily status over 365 days".* However, match injury prevalence is regarded as the percentage of players unavailable for match participation because of injury and may be calculated according to different cricket match formats (test, one day and T20) or a combination thereof.[134]

Relative risk (RR), confidence intervals (95% CI) and standard error of measurement (SEM) of injury incidence were assessed using the equations proposed by Knowles et al (2006.)[136] All cricket squads were analysed and a comparison between the national squad and franchise squads (provincial teams) was assessed, as level of participation is known to influence shoulder injury risk.[72]

Descriptive variables and the pre- and post-season KJOC scores were analysed using Statistica version 13.3. All variables were screened for normality using the Shapiro Wilk Test. As data were not normally distributed with equal variance, a Mann-Whitney U test was used to determine potential group differences for both injury history and injury sustained in the 2016/2017 season.

Lastly, the RR for the categorical variable of previous shoulder injury was calculated using the equation recommended by Bahr and Holme (2016).[137] Relative risk was determined as: *(Uninjured in season, with history of previous injury/Injured in season, with history of previous injury)/(Uninjured in season, with no history of previous injury/Injured in season with, no history of previous injury.* Statistical significance as accepted at $p<0.05$. Data are presented as mean ± standard deviation.

3.4 RESULTS

Eighty-two percent of elite senior male South African cricketers (106 of 129 cricketers) volunteered to participate in, and completed this study, with a mean age of 26.6 ± 4.2 years (Table 3.1). The cricketing cohort consisted of 17 (16.04%) left and 89 (83.96%) right handed players from all cricket disciplines. A total of 19 cricketers sustained a shoulder injury during the 2016/2017 season (National squad = 5; franchise squads = 14). Eighteen non-traumatic injuries occurred to the dominant shoulder and one traumatic injury to the non-dominant shoulder. The latter was sustained by a franchise cricketer when diving and landing on the shoulder to field a ball during training, and resulted in a loss of one match day only.

Table 3.1: The descriptive variables of participants used in this study and a summary of shoulder injury incidence and prevalence, according to squad representation.

Squad	All (n=106)	National (n=15)	Franchise (n = 91)
Age (years)	26.6 ± 4.2	28.9 ± 3.7	26.3 ± 4.2
Dominance (Left/Right)	17/89	2/13	15/76
Speciality (n)			
Fast Bowler	51	7	44*
Spin Bowler	26	3	23
Bat	29	5	24
Previous History of Shoulder Injury (Yes/No)	34/72	6/9	28/63*
Shoulder Injury Sustained in 2016/2017 Season (Yes/No)	19/87	5/10	14/77*
Match Incidence			
5-day	n/a	4.1	-
4 day	n/a	-	0.4
One Day	1.0	-	1.3
T20	1.1	-	1.1
All matches	0.9	2.6	0.6
Annual Incidence	0.19	3.04	0.18
Match Prevalence			
5-day		10.7	-
4 day	0.02	-	0.63
One Day	0.2	6.7	0.06*
T20	0.1	6.7	0.0
All matches	0.2	10.8	0.03
Annual Prevalence	1.1	7.1	0.1

*One participant sustained a traumatic shoulder injury to the non-dominant side.

Of the entire cricketing cohort a total of 34 cricketers had a history of previous shoulder injury (National squad = 6; franchise squads = 28). Of those cricketers who sustained a shoulder injury during the 2016/2017 season, nearly half (47%; 9/19) had a history of previous shoulder injury. Eight of these cricketers sustained 5 new injuries and 3 recurrent injuries to the same shoulder previously injured; while a single new traumatic injury occurred to the opposite shoulder. The risk of sustaining a shoulder injury in a cricketer is 1.91 (95% CI: 1.73-2.15) times greater with a history of previous shoulder injury. This relative risk ratio for previous injury is higher for the national squad (RR = 2.25; 95% CI: 1.88-2.62), compared to the franchise squads (RR = 1.90; 95% CI: 1.71-2.14).

A detailed description of injury incidence, prevalence and the variables associated with shoulder injury in the season, are presented in Table 1 and 2 respectively. Eighteen percent (95% CI: 11-25%) of elite South African cricketers sustained a shoulder injury in the 2016/2017 season, at a rate of 0.19 shoulder injuries per player per year. The national players were no more likely to sustain an injury than the franchise players (RR = 1.27; 95% CI: 0.34-1.34).

Eleven injuries occurred during matches, while eight occurred during cricket specific training. Most injuries (58%) were sustained while throwing, with these occurring during fielding. A clinical diagnosis of rotator cuff muscle tendinopathy (55%) and/or strain (33%) was most frequently reported.

Thirty-two percent of cricketers who sustained a shoulder injury were unavailable for match selection. These match time-loss injuries caused approximately 21 ± 24 (range of 5-50) and 2 ± 1.5 (range of 1-4) days of missed cricket in the national and franchise squads, respectively. Sixty eight percent of cricketers who sustained a shoulder injury were able to continue with training and match participation. One hundred percent of non-time-loss injuries impacted primary skill (i.e.: bowling, batting) while 80% impacted fielding. Of the injuries that impacted fielding, 58% caused changes to throwing technique and 21% to fielding position.

The National squad demonstrated the highest shoulder match injury incidence during the five-day tests (4.1 shoulder injuries per 1000 player hours). Conversely, the highest shoulder match injury incidence for the franchise squads was found in one day (1.3 shoulder injuries per 1000 player hours) and T20 (1.1 shoulder injuries per 1000 player hours) formats, respectively.

Table 3.2: The descriptive variables of shoulder injuries sustained during the 2016/2017 season according to team representation

Squad	**All (n=19)**	**National (n=5)**	**Franchise (n=14)+**
Speciality			
Fast Bowler	8	3	5*
Spin Bowler	4	-	4
Batsmen (incl. WK)	7	2	5
Occurrence of injury			
Practice	8	1	7*
Domestic Matches			
T20	1	-	1
ODI	3	-	3
4-Day test	3	-	3
International Matches			
T20	-	-	-
ODI	-	-	-
5-day (test)	4	4	-
Activity associated with injury occurrence			
Bowling	4	2	2
Batting	1	-	1
Field – Throw	11	2	9
Fielding – Catch	-	-	-
Fielding – Dive	3	1	2*
Performance negatively affected by injury			
Speciality	13	5	8*
Throwing Action	11	3	8
Field placement	4	3	1
Selection	6	2	4*
Type of Injury*			
Muscle Strain	6	3	3
Labral tear	1	-	1*
Fracture	1	1	-
Tendinopathy	10	1	9
Capsular Sprain	1	-	1
Mode of Onset			
Acute	9	3	6
Gradual	10	2	8

+One squad included in the franchise cohort did not sustain any shoulder injuries during the 2016/2017 season.

*Non-dominant shoulder injury to one participant

**Injured players were followed up with special investigations including x-ray, MRI or musculoskeletal ultrasound

Figure 3.1 summaries the pre- and post-season KJOC scores according to group mean, injury history and injury sustained in the 2016/2017 season. Overall, this cohort of cricketers (n=106) demonstrated low mean pre- (78.5 ± 15.6%) and post-season (81.2 ± 17.1) KJOC scores (Figure 3.1A). The pre-season KJOC score was significantly lower (r^2=0.106, p=0.001) for cricketers who had sustained a previous shoulder injury (n=34), compared to those with no history of previous injury (n=72), (Figure 3.1B). Similarly, the post-season KJOC Scores were significantly lower (r^2=0.112, p<0.001) for cricketers who sustained a shoulder injury in the 2016/2017 season (n=19), compared to those with healthy shoulders (n=87), (Figure 3.1C). Finally, cricketers who sustained a shoulder injury in the 2016/2017 season (n=19) and had a history of previous shoulder injury (n=9) demonstrated significantly lower pre-season KJOC scores (r^2=0.044, p=0.03), compared to those with no history of previous injury (n=10), (Figure 3.1D).

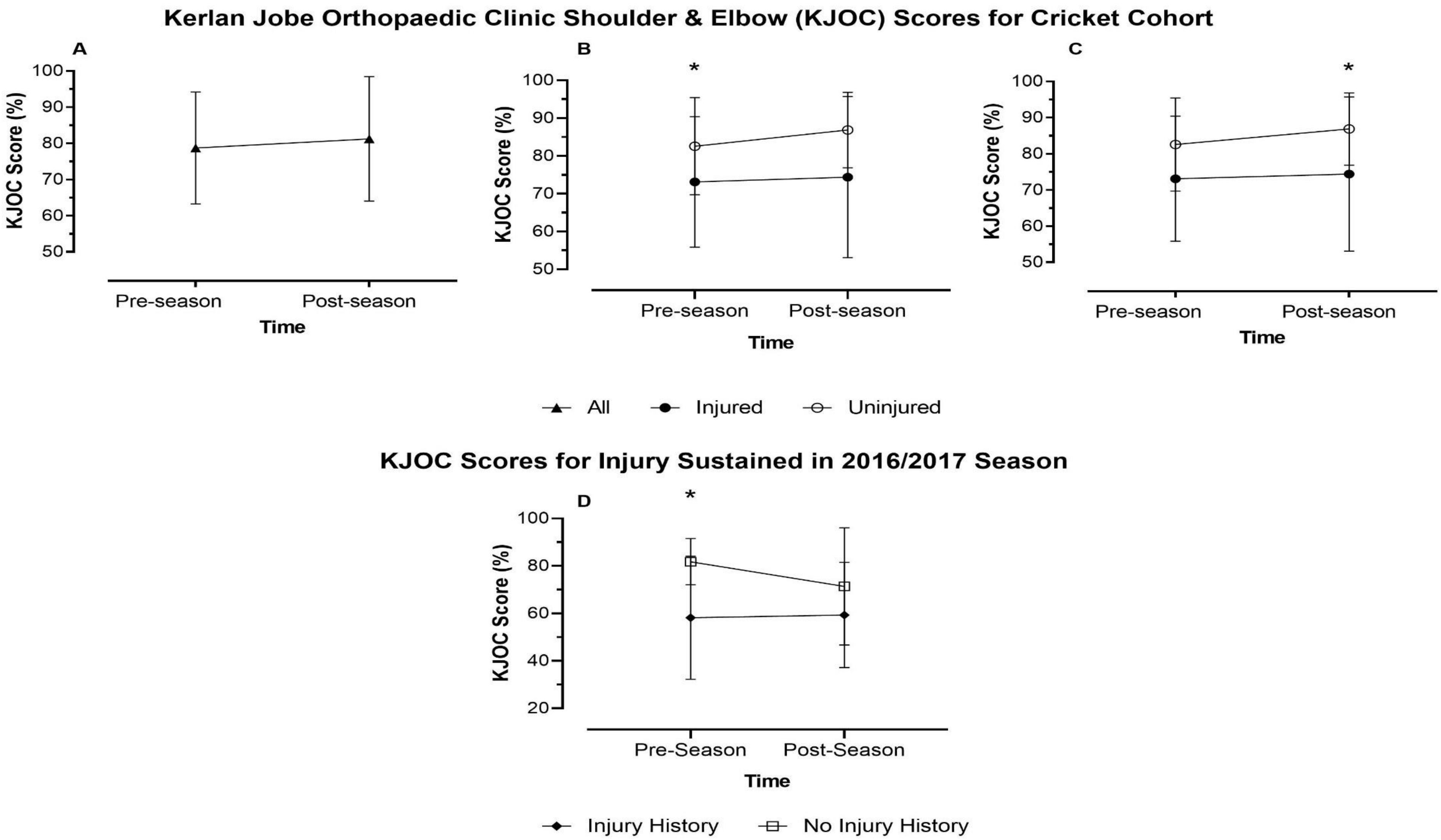

Figure 3.1: A. Group KJOC scores over the 2016/2017 season (n=106). B. KJOC Scores over the 2016/2017 season between cricketers with a history of shoulder injury (n=34) and without (n=72). C. KJOC Scores between cricketers that sustained a shoulder injury in the 2016/2017 season (n=19) and those who did not (n=87). D. KJOC Scores for shoulder injury sustained in 2016/2017 season (n=19) with a history of previous shoulder injury (n=9) and without (n=10). *group difference (p<0.03).

3.5 DISCUSSION

Shoulder injuries in elite South African cricketers were reported by 18% of players over the 2016/2017 season. While this result is in agreement with the 15-36% previously reported in recent injury surveillance studies conducted on elite junior Australian,[32] as well as junior[7] and professional county[31] English cricketers; it is higher than the 5% originally reported for South African cricketers.[27] The disparity in number of shoulder injuries reported in this cohort compared with other studies can be attributed to the fact that only time-loss shoulder injuries were reported in the previous study.[27] Had this description been used in the current study, an injury incidence of 5% would have been found, as only 32% (6 of 19 shoulder injuries) of shoulder injuries sustained by elite South African cricketers during the 2016/2017 season, resulted in time-lost to match participation.

Throwing has been identified in the literature as the primary activity associated with shoulder injury[6,27-31,33] and the rotator cuff tendons as the structures most frequently injured.[27-30,34] These findings are supported by this study. Notably, the most frequent shoulder injuries in this study were tendinopathies (55%; 10/18 non-traumatic injuries) followed by muscle strains (33%; 6/18 non-traumatic injuries). The impact of shoulder injury on the performance of specific skills, such as batting and bowling, was found to be similar to the 46-67% reported in current literature.[7,31] Conversely, the impact of shoulder injury on fielding position, was substantially lower than the 58-60% noted in previous studies.[7,31] Only 21% of elite South African cricketers with a shoulder injury, indicated that fielding position was altered, whereas 58% indicated throwing technique was altered. It is plausible that the adjustment to throwing technique allowed injured cricketers to field in their usual positions. The impact of changes in fielding position or throwing technique on performance during a match could not be evaluated in this study, but does raise concerns about throwing performance, particularly in the T20 format of the game which is shorter, more explosive and may require greater throwing frequency and intensity.

In this investigation, consistent with studies involving baseball players,[131,138] the KJOC score effectively distinguished between cricketers playing with pain, without pain or not playing at all due to pain. Thus, it is suggested that future injury surveillance studies include a measure of functional impediment in association with pain, in the definition of injury.

Substantially lower pre-season KJOC scores were achieved when compared to the normative value of 90%, recommended by Kraeutler et al (2013)[132] for baseball players. This finding indicates that despite the lack of reported shoulder injury, a number of cricketers did not report 100% shoulder functional ability. Not only is this sub-optimal shoulder function correlated with an increased risk of injury, but it can potentially impact performance.

This emphasises the necessity to investigate the musculoskeletal profile of a cricketer's shoulder, throwing kinematics, as well as the potential effect of these respective variables on shoulder injury risk.

Eight shoulder injuries occurred during training, while 11 occurred during matches. The slightly higher number of shoulder injuries sustained during matches, could be associated with throwing intensity. A match situation (limiting the number of runs scored by the opposition or effecting a run-out) may require throws to be performed with greater force and velocity, than those performed in training. This proposed higher intensity of throwing may be responsible for the slightly higher incidence of shoulder injuries in matches when compared to practices, found in this study. Orchard et al (2017)[67] described a similar trend for hamstring injuries related to sprinting intensity in the different formats of cricket matches.

Notably, it has been suggested that a one-week spike in throwing workload may trigger shoulder injuries.[3] In addition, when cricketers exceed 75 throws per week, shoulder injury risk has been found to increase by 1.73 times.[3] This weekly throwing load is often exceeded when considering the number of throws performed in fielding drills or batting throw-down sessions and may be further exacerbated by warm-up sessions specifically when playing multiple day matches or limited over matches in quick succession of each other. Throwing exposure in terms of training hours or number of throws per training session was not investigated in this study but the poor mean KJOC scores for this cohort suggest that throwing load during training or match sessions should be monitored in a similar fashion to bowling load during a net session. Further, it is suggested that competitive small-sided cricket games, such as "Battlezone"[139] be implemented in cricket training sessions to ensure throwing intensity mimics the requirements of matches.[140]

The overall injury prevalence of the entire cricket cohort illustrates similar injury risk across all formats of the game. This is in contrast to the trend reported in the literature with injury risk highest in T20 matches, followed by one-day and then multiple day (5-day and 4-day) matches.[72] Interestingly, the national squad was found to be more susceptible to shoulder injury in the longer formats of the game, while the opposite is true for the franchise squads. A comparison of both annual injury incidence and prevalence between national and franchise squads (Annual incidence: 3.04 ± 0.0 vs 0.18 ± 2.32 shoulder injuries per player per year, $p=0.09$; combined match prevalence: 7.1 ± 0.0% vs 0.1 ± 0.15%, $p<0.0001$) highlights that injury risk is similar, yet injury frequency increases with progression in level of participation and play. This may be attributed to the higher intensity and workloads of training and matches,[72] longer season duration, as well as participation in professional tournaments such as the Indian Premier League and Australian Big Bash League.

Cricketers with a greater risk of shoulder injury were those who had previously sustained a shoulder injury. This agrees with findings previously reported by Stretch (2003)[27] and Giles and Musa (2008,)[7] highlighting history of previous shoulder injury as a significant risk factor. It is possible that the shoulder may demonstrate a functional instability following initial injury, similar to that described for lateral ankle ligament sprains.[141] Failure to detect and adequately rehabilitate the associated neuromuscular[142] and proprioceptive[143] deficits known to occur with shoulder injury, may result in the development of latent pathology or irreversible structural damage to the shoulder. Consequentially, changes to movement sequencing and the biomechanical patterns of throwing and/or bowling are thought to occur and may be exacerbated by weak GH external rotators and scapula dyskinesis.[144] Ultimately, the load on the shoulder joint is attenuated. Further research is required to determine the factors associated with recurrent shoulder injuries in cricket.

This study was conducted over a single season and utilised a small sample. Future studies should consider a multi-centre study of cricketers performing at equivalent levels, as well as a longer period of injury surveillance. These suggestions will improve statistical power and allow for player speciality/position comparisons with shoulder injury risk. Although this study based clinical diagnosis on the WHO ICD list,[135] diagnostic error may have occurred where medical staff have less clinical experience in cricket. Thus, the diagnostic accuracy and inter-rater reliability of cricket medical staff needs to be determined. Finally, the possibility that cricketers completed the KJOC score inaccurately needs to be considered. This may have occurred due to fear of potential loss of national/franchise contracts through injury, or as a result of the time-elapsed between injury sustained and completion of the post-season KJOC score. Therefore it is suggested that future studies determine whether pre- and post-season KJOC scores can be effectively compared to determine shoulder injury risk.

3.6 CONCLUSION

This study is the first to report both time-loss and non-time-loss shoulder injury in elite South African cricketers. A history of previous shoulder injury and a decreased functional ability score for the shoulder were associated with an increased risk of injury. Despite injury, most cricketers are generally able to continue participating in practices and matches, by altering their throwing technique or fielding position which may influence performance. Consequentially, the importance of documenting all injuries, irrespective of potential time lost to practices and matches; as well as a measure of function, in the definition used for shoulder injury surveillance studies in cricket, is highlighted.

Practical Implications

- When combining both time-loss and non-time-loss injuries, 18% of elite South African cricketers sustained a shoulder injury in the 2016/2017 season.
- The incidence of non-time-loss shoulder injury in elite South African cricketers is 13%.
- Non-time-loss injuries impacted primary skill in 100% of cricketers with shoulder injury, while 80% also reported a negative impact on fielding performance.
- A baseline measure of shoulder function should be determined at pre-season, repeated monthly during the season and/or at the time of injury.

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Conflicts of interest

No conflicts of interest.

CHAPTER 4 - THE CRICKETER'S SHOULDER: NOT A CLASSIC THROWING SHOULDER

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For the purposes of this thesis figures and tables as well as their captions have been placed in the appropriate places within the text of the article and general formatting is aligned with the requirements of the Doctoral Degrees Board, University of Cape Town.

A detailed copy of the methodology used for all musculoskeletal variables described in supplementary table 4.1 can be found in Appendix II.

4.1 ABSTRACT

Objectives: To describe the musculoskeletal adaptations inherent to the cricketers' shoulder and determine potential predictors of shoulder injury in elite South African cricketers.

Design: Prospective longitudinal cohort study

Setting: Non-clinical, at national cricket indoor training venues

Participants: One hundred and six elite cricketers, representing 82% of the South African national and franchise teams, consent. A total of 105 cricketers (27±4 years) were eligible for participation in this study.

Main Outcome Measures: A pre-season shoulder screening battery including a shoulder function questionnaire, two ultrasonographic shoulder measurements and 14 musculoskeletal tests including pain provocation, range of motion, strength and flexibility was assessed. Non-contact dominant shoulder injuries were documented throughout the 2016/2017 season.

Results: The musculoskeletal profile of a cricketer's shoulder is described. 17% (95%CI: 9-24%) of cricketers sustained an injury during the 2016/2017 season. Two of the 17 screening tests predicted seasonal dominant shoulder injury ($p<0.05$): a dominant supraspinatus tendon thickness ≥5.85mm (sensitivity: 72%, specificity: 63%) and non-dominant pectoralis minor length ≤12.85cm (sensitivity: 83%, specificity: 55%).

Conclusion: The musculoskeletal adaptations inherent to cricketing shoulders are distinctly different to the classic *"thrower's shoulder"* described in baseball. A thickened dominant supraspinatus tendon and a shortened non-dominant pectoralis minor muscle are risk factors for developing shoulder injury in this group. This identifies the need to investigate preventative strategies (strengthening/flexibility) and throwing workload management in cricketers with shoulder injury.

Keywords: Cricket, thrower's paradox, shoulder injury, risk factors, musculoskeletal screening

4.2 INTRODUCTION

The van Mechelen model of sport injury prevention[26] states that only once injury incidence and severity is known, can risk factors of injury be assessed. The incidence of shoulder injuries has been reported as 5-36% of all injuries sustained by cricketers.[7,28,31] Numerous intrinsic risk factors for shoulder injury have been identified in overhead throwing athletes including amongst others, glenohumeral internal rotation deficit (GIRD);[89,90] total glenohumeral (GH) rotational range of motion (ROM) loss[94,145]; scapula dyskinesis;[89,90] variances in the acromiohumeral (AHD) distance;[116,126,146] and reduced hip mobility and strength.[20,22] Extant cricket literature has primarily focused on the GH rotational ROM[7] and scapula positioning[32] alterations as a probable association with shoulder pain

Musculoskeletal screening protocols pre-season/participation have been successful in identifying a variety of injury risk factors in football,[147,148] basketball,[147,148] volleyball[147] and running.[149] Interestingly, only two studies have positively determined risk factors for trunk, back and lower limb cricket injuries.[66,150] Currently, no study has investigated the relationship between musculoskeletal screening and upper limb cricket injuries. Further, insufficient knowledge of the risk factors associated with the development of shoulder pain and/or injury in cricketers exists; which if identified could allow for better rehabilitation and prevention strategies.

The dominant shoulder of overhead throwing athletes (e.g. baseball, cricket, tennis, volleyball, swimming) is thought to require a delicate balance between stability and mobility to achieve optimal performance.[40] This balance is termed the *"thrower's paradox"* that contributes towards shifting the arc of GH rotational ROM with the aim of increasing external rotation ROM,[40] while maintaining a total 180° GH rotational ROM;[41] an adaptation essential to generating ball velocity when throwing overhead.[10,11] Cricketers could exhibit the *"thrower's paradox"* as found in baseball, as the overhead baseball pitching motion has been likened to the overhead throwing motion in fielding in cricket.[35] However, limited data exists to support this.[7] Therefore, it is questionable whether these athletes develop a true *"thrower's paradox"*, and the associated musculoskeletal adaptations responsible for the alteration in the arc of GH rotational ROM, potentially influencing overhead throwing performance.

The development of the *"throwers paradox"* is primarily thought to occur as a result of the increased humeral retroversion angle (~45°) noted in baseball research.[9,74] However, this osseous adaptation is absent in cricketers,[75] suggesting that the "pseudolaxity"[34] created by the contracture of the posterior shoulder complex and excessive stretching of the anterior shoulder capsule associated with repetitive overhead throwing, may allow cricketers to alter the arc of GH rotational ROM.

Interestingly, these soft tissue adaptations promote excessive anterio-superior humeral head migration,[12,13] leading to the development of shoulder impingement and pain.[14-16] Long-term injury surveillance studies have reported that shoulder impingement,[5,6] scapula dyskinesis[5] and GIRD[5] are associated with the development of rotator cuff musculature and/or tendinous injuries in cricketers.[27,29,34]

To date, no study has investigated the relationship between ultrasonographic measurement and musculoskeletal screening tests of the shoulder, as well as hip mobility and strength measures; and shoulder injury in cricket. Thus, this study aims to describe the musculoskeletal adaptations of a cricketer's shoulder to determine whether cricketers present with a similar *"thrower's paradox"* to that known of the baseball population. Secondly, to determine if any variables were associated with either a seasonal or historical shoulder injury in cricketers. Lastly, to determine if any of these are predictors of shoulder injury.

4.3 METHODS

4.3.1 Participants

During annual pre-season musculoskeletal screening, all cricketers representing a South African franchise or senior national team during the 2016/2017 season were invited to participate in this study. Participants were included in this study if they were 18 years of age or older, performed at least two cricket specific (net), one fielding training and one to two fitness sessions per week. In addition, participants were expected to play in at least one format (Four day, One day or T20) of cricket matches throughout the 2016/2017 season. All eligible participants were informed of the experimental risks and signed an informed consent document prior to investigation. Ethical approval was obtained from the institutional research ethics committee (HREC: 364/2016).

All cricketers were tested within a two week period during September, at the start of the domestic cricket season. Each cricket squad (13-22 cricketers/squad) was assessed on a single day, with no other formal training scheduled for that day. As the National team play all year-round and lack a specific pre-season, testing was conducted at a training camp coinciding with the start of the domestic season. Injury data were collected over the subsequent six months (October-March) of the 2016/2017 domestic cricket season. Only non-traumatic injuries to the dominant shoulder were included in data analysis, as musculoskeletal risk factors are most likely associated with overuse injuries.[151]

4.3.2 Measurement Procedures

Participants completed a questionnaire for descriptive data, training, competition and injury history, prior to the pre-season shoulder screening protocol. This included a shoulder function questionnaire specific to overhead athletes.[131] A battery of screening tests were conducted and included two ultrasonographic shoulder measurements, eleven shoulder and three hip specific tests. A summary of the measurement protocol, testing positions, intra-rater reliability and sequence of testing is provided in Supplementary Table 4.1.

Digital inclinometers (Digi-Pas DWL80E, Digipas Technologies, Inc., Dundee, England) were used to measure GH and hip rotation, scapula upward rotation and GH horizontal adduction ROM (PSC stiffness), with an accuracy of 1°. Isometric muscle strength of the upper trapezius (UT), serratus anterior (SA), lower trapezius (LT), GH internal (GHIR) and external (GHER) rotators and gluteus medius (GM) muscles were determined using a hand-held dynamometer (MicroFET 2, Hoggan Scientific, LCC., Salt Lake City, Utah, USA). A calliper (Mastercraft Vernier Calliper, Mastercraft Tools, Johannesburg, South Africa) was used to measure PM length (PML) and lastly a diagnostic ultrasound (M7, Shenzen Mindray Bio-medical electronics Co., Ltd., Guangdong, China) was used to measure AHD and supraspinatus tendon thickness (SsT).

Each test was repeated and an average of the two scores were recorded. All tests were performed on the non-dominant side, prior to dominant side testing. All testing procedures were reliable (ICC=0.64-0.99; except the pain provocation tests, κ=1) (Supplementary Table 4.1), repeatable and performed by the same author (MD) who was familiarised with the respective testing protocols.

4.3.3 Statistical Analysis

Based on data from previous studies which have measured shoulder pain,[32] the primary outcome measure of this study, sample size was estimated for an error probability of 0.05 and statistical power of 80%. Using a small meaningful difference of 10.1 and a standard deviation of 8, a sample of 25 participants was deemed sufficient. However, to ensure statistical significance of all variables measured, a sample in excess of 65 participants was required as demonstrated in Supplementary Table 4.2.

Pre-season shoulder screening data were analysed using SPSS version 24 (IBM, Armonk, New York, USA). Descriptive statistics were calculated for all variables and all variables screened for normality using the Shapiro Wilk test. Where data were normally distributed with equal variance, independent t-tests were performed to determine group differences for both injury history and injury sustained in the 2016/2017 season.

However, data not normally distributed were analysed using the Mann-Whitney U test to determine potential differences between groups, as mentioned previously. A binary logistic regression (adjusting for unresolved injury symptoms) was performed, followed by a Receiver operating Curves (Roc) analysis to determine predictive capabilities of the pre-season shoulder screening tests on shoulder injuries that were sustained during the 2016/2017 season. Statistical significance and cut-off for prediction was set at $p<0.05$ (for a sensitivity ≥70%). Sensitivity was defined as the probability that the test result will be positive when shoulder injury is present; whereas specificity was regarded as the probability that the test result will be negative when the shoulder is uninjured.[152] Data are presented as mean ± standard deviation unless otherwise stated.

4.4 RESULTS

4.4.1 Participants

One cricketer sustained a traumatic injury to the non-dominant shoulder and was excluded from this study. Therefore, 105 cricketers were eligible to participate in this study (27±4 years), where 17% (95%CI: 9–24%) of this group sustained an injury during the 2016/2017 season. Thirty three cricketers reported a history of previous shoulder injury and 15 reported symptoms at the start of the season (Table 4.1). Cricketers with a history of previous shoulder injury exhibited lower pre-season KJOC scores ($Z=-3.18$; $p=0.001$) and less dominant hip internal rotation ROM ($Z=-2.01$; $p=0.045$), compared to those with no previous shoulder injury (Table 4.2). Irrespective of injury or a history there-of, pain provocation was elicited in 5-19 dominant shoulders depending on the test used.

4.4.2 Descriptive Profile of the Cricketer's Shoulder

All pre-season shoulder screening variables are presented in Table 4.2. These findings indicate that this cohort of elite cricketers presents with GIRD; a loss of total GH rotational ROM; a consistently downwardly rotated scapula from rest to 90° GH elevation; relatively normal UT strength, poor SA, GHIR and GHER strength, yet greater LT strength; relatively normal PML but substantial PSC stiffness; greater AHD measurement and relatively normal SsT measurement; a bilateral deficit in hip external and total rotational ROM, as well as GM muscle weakness.

Table 4.1: Description of the ordinal characteristics and significant musculoskeletal variables relating to injury history, for participants in the injured (n = 18) and uninjured (n = 87) groups, respectively. Data are expressed as mean ± standard deviation.

Variable		**All (n = 105)**	**Injured (n = 18)***	**Uninjured (n = 87)**
Age (years)		27 ± 4.2	27.5 ± 3.9	26.5 ± 4.2
Dominance	Left	17	2	15
	Right	88	16	62
Speciality	Fast Bowler	50	7	43
	Spin Bowler	26	4	22
	Batsman	29	7	22
History of previous shoulder injury	Yes	33	8	25
	No	72	10	62
Symptoms of previous injury present at start of season	Yes	15	6	9
	No	18	2	16
Symptoms on Hawkin's Kennedy Test	Dominant Shoulder	19	6	13
	Non-dominant Shoulder	7	1	6
Symptoms on Jobe Test	Dominant Shoulder	16	4	12
	Non-dominant Shoulder	4	2	2
Symptoms on Full Can Test	Dominant Shoulder	5	-	5
	Non-dominant Shoulder	4	1	3

*One participant excluded as shoulder injury sustained was traumatic and to the non-dominant side.

4.4.3 Effect of Injury on Musculoskeletal Screening Variables

Only 3 of 17 musculoskeletal screening variables were different for cricketers who sustained seasonal injuries, after adjusting for pre-existing injury (Table 4.2). Participants who sustained a shoulder injury in the season had significantly thicker dominant SsT (p=0.011), shorter non-dominant PML (p=0.017) and lower post-season KJOC scores (p<0.001), when compared to the uninjured group.

4.4.4 Potential Predictive Risk Factors for Shoulder Injury in Cricketers

Dominant shoulder SsT (AUC=0.688; 95% CI: 0.561-0.814) and non-dominant shoulder PML (AUC=0.704; 95% CI: 0.584-0.823) were found to be predictors of in-season shoulder injury (Table 4.3). In addition, the cut-off values for dominant shoulder SsT ≥5.85mm (sensitivity: 72%, specificity: 63%) and non-dominant PML ≤12.85cm (sensitivity: 83%, specificity: 55%) demonstrated high sensitivity but low specificity.

Table 4.2: Description of the musculoskeletal variables for this cohort of cricketers (n = 105), in the injured (n=18) and uninjured (n=87) groups, respectively; compared to the known normative values for **A. The Shoulder Joint Complex** and **B. The Hip Joint.** Data are expressed as mean ± standard deviation or as median (range).

A. The Shoulder Joint Complex

Variable	Shoulder	All (n=105)	Injured (n=18)	Uninjured (n=87)	Reference Data
Pre-Season KJOC Score (%)		84.5 (36.4 – 100)	78.7 (40.0 – 92.7)*	84.8 (36.4 – 100)*	90[132]
Post-Season KJOC Score (%)		85.6 (19.1 – 100)	66.5 (19.1 – 100)**	86.8 (47.2 – 100)**	
AHD (mm)	Dominant	12 (7.7 – 20.7)	12.1 (8.8 – 17.6)	12.1 (7.7 – 20.7)	10.3 ± 1.0[118++]
	Non-dominant	11.9 ± 2.3	11.3 ± 2.2	12.0 ± 2.4	11.0 ± 0.8[118++]
SsT (mm)	Dominant	5.6 ± 1.1	6.1 ± 1.0**	5.4 ± 1.1**	4.6 ± 1.9 mm[146+++]
	Non-dominant	5.6 ± 1.1	5.7 ± 1.1	5.6 ± 1.0	
GH IR ROM (°)	Dominant	40.0 (0 – 96.2)	34.2 (23.7 – 96.2)	40.9 (0 – 62.6)	56.6 ± 12.5[40+]
	Non-dominant	35.1 (10.1 – 88.1)	37.6 (21.0 – 88.1)	35.0 (10.1 – 79.0)	68.6 ± 12.6[40+]
GH ER ROM (°)	Dominant	90.0 (39.4 – 124.8)	96.8 (39.4 – 115.1)	90.0 (67.5 – 124.8)	108.9 ± 9.0[40+]
	Non-dominant	89.5 (30.6 – 162.6)	90.0 (30.6 – 123.0)	89.5 (36.6 – 162.6)	101.9 ± 5.9[40+]
Total GH Rot ROM (°)	Dominant	135.6 (67.5 – 167.4)	133.9 (106.5 – 163)	136.1 (67.5 – 167.4)	165.5 ± 14.4[40+]
	Non-dominant	133.6 (54.6 – 179.5)	138.1 (54.6 – 167.5)	131.3 (57.7 – 179.5)	170.4 ± 10.5[40+]
Upward scapula rotation at rest (°)	Dominant	-3.6 (-23.1 – 11.0)	-1.6 (-21.3 – 6.1)	-4.0 (-23.1 – 11.0)	6.4 ± 4.7[40+]
	Non-dominant	-12.6 (-22.7 – 11.0)	-12.3 (-21.9 – 5.6)	-12.8 (-22.7 – 11.0)	4.7 ± 4.1[40+]
Upward scapula rotation at 45° GH Abd (°)	Dominant	1.2 (-24.5 – 9.3)	0.8 (-24.5 – 6.4)	1.2 (-20.8 – 9.3)	Unknown
	Non-dominant	-5.8 (-22.8 – 15.9)	-8.9 (-22.7 – 9.7)	-5.2 (-18.6 – 15.9)	
Upward scapula rotation at 90° GH Abd (°)	Dominant	10.4 (-13.0 – 28.7)	9.5 (-13.0 – 9.3)	10.8 (-1.9 – 28.7)	14.2 ± 6.5[40+]
	Non-dominant	5.0 (-12.8 – 22.4)	5.1 (-12.8 – 18.5)	5.0 (-11.6 – 22.4)	10.1 ± 6.1[40+]
Upward scapula rotation at 120° GH Abd (°)	Dominant	22.2 (7.9 – 44.9)	23.0 (7.9 – 40.2)	22.2 (11.1 – 44.9)	22.4 ± 6.3[40+]
	Non-dominant	17.2 (3.7 – 42.0)	15.4 (4.8 – 36.5)	17.2 (3.7 – 42.0)	20.0 ± 5.8[40+]
UT strength (N)	Dominant	150.0 (106.1 – 330.6)	154.8 (130 – 330.6)	148.4 (106.1 – 260.2)	158.6 ± 47.7[113++]
	Non-dominant	144.6 (81.8 – 299.9)	151.0 (116.3 – 299.9)	143.0 (81.8 – 199.5)	148.4 ± 49.6[113++]
SA strength (N)	Dominant	133.2 (90.3 – 331.7)	128.3 (91.8 – 331.7)	135.5 (90.3 – 238.7)	154.8 ± 61.9[113++]
	Non-dominant	147.7 (60.3 – 299.4)	135.5 (94.5 – 299.4)	149.5 (60.3 – 255.6)	136.8 ± 44.8[113++]
LT strength (N)	Dominant	70.7 (0.0 – 136.3)	66.0 (0 – 96.4)	72.3 (38.0 – 136.3)	67.2 ± 18.6[153+]
	Non-dominant	69.0 (38.0 – 124.3)	62.5 (46.5 – 96.5)	69.4 (38.0 – 124.3)	59.6 ± 12.0[153+]
GH IR strength (N)	Dominant	132.7 (70.5 – 312.6)	124.3 (74.3 – 187.8)	133.5 (70.5 – 312.6)	178.5 ± 38.8[153+]

	Non-dominant	130.6 (72.7 – 408.0)	125.2 (89.9 – 161.0)	130.6 (72.7 – 408.0)	170.9 ± 35.8[153+]
GH ER strength (N)	Dominant	109.5 ± 26.3	100.7 ± 28.2	111.3 ± 25.7	147.6 ± 36.0[153+]
	Non-dominant	102.0 ± 23.9	98.6 ± 17.4	102.7 ± 25.0	168.1 ± 40.1[153+]
GH ER:IR	Dominant	0.83 (0.17 – 1.5)	0.82 (0.47 – 0.99)	0.83 (0.17 – 1.50)	0.71 – 1.08[154+]
	Non-dominant	0.80 ± 0.17	0.80 ± 0.20	0.80 ± 0.17	
Pec Minor length (cm)	Dominant	12.7 ± 1.0	12.6 ± 1.1	12.7 ± 1.0	11.7 ± 1.2[113++]
	Non-dominant	12.8 (10.5 – 15.1)	12.2 (10.7 – 15.0)**	13.1 (10.5 – 15.1)**	12.9 ± 1.3[113++]
PSC flexibility (°)	Dominant	13.8 ± 6.5	14.0 ± 7.5	13.7 ± 6.3	45.9 ± 5.9[155+]
	Non-dominant	21.5 ± 8.5	23.7 ± 7.8	21.0 ± 8.6	24.1 ± 9.2[155+]

B. The Hip Joint

Variable	Hip	All (n=105)	Injured (n=18)	Uninjured (n=87)	Reference Data
Hip IR ROM (°)	Dominant	23.0 (12.5 – 52.0)	22.4 (12.8 – 30.9)*	23.1 (12.5 – 51.9)*	34.6 ± 4.4[156+]
	Non-dominant	22.4 (7.0 – 48.0)	24.1 (13.3 – 35.7)	21.3 (7.0 – 48.0)	34.4 ± 6.1[156+]
Hip ER ROM (°)	Dominant	32.8 (14.4 – 60.4)	30.7 (14.4 – 46.8)	33.0 (15.1 – 60.4)	41.0 ± 6.3[156+]
	Non-dominant	33.6 (15.1 – 68.1)	31.9 (15.1 – 46.0)	34.0 (19.5 – 68.1)	40.9 ± 8.1[156+]
Total Hip Rot (°)	Dominant	55.4 (34.0 – 112.3)	53.2 (33.9 – 77.7)	56.1 (37.1 – 112.3)	75.6 ± 5.9[156+]
	Non-dominant	56.1 (31.2 – 116.1)	55.8 (31.2 – 74.2)	56.1 (36.0. – 116.1)	75.3 ± 7.8[156+]
GM strength (N)	Dominant	190.2 (108.1 – 281.5)	190.2 (134.6 – 277.0)	190.2 (108.1 – 281.5)	406.0 ± 61.8[156+]
	Non-dominant	180.6 (105.4 – 296.7)	180.7 (135.9 – 262.3)	180.6 (105.4 – 296.7)	410.9 ± 70.6[156+]

[+]Based on baseball pitchers; [++]Based on other overhead athletes e.g. tennis, volleyball; [+++]Based on healthy, inactive people

*Significantly different between cricketers with and without a history of previous shoulder injury ($p < 0.05$)

**Significantly different between cricketers who sustained a seasonal shoulder injury and those who did not

Table 4.3: Receiver Operating Characteristics (RoC), cut-off values, sensitivity and specificity for continuous variables showing significant differences for injury sustained in 2016/2017 season

Variable	Area	Std Error	Asymptotic Sig.	Asymptotic Sig. 95% CI		Cut-off	Sensitivity (true positive rate)	Specificity (true negative rate)
				Lower	Upper			
Dominant SsT	0.688	0.064	0.012	0.561	0.814	≥ 5.85mm	72%	63%
Non-dominant PML	0.704	0.061	0.007	0.584	0.823	≤ 12.85cm	83%	55%

4.5 DISCUSSION

4.5.1 Descriptive Profile of the Cricketer's Shoulder

The primary outcome of this study was that cricketers do not completely present with the classic "*thrower's paradox*". Specifically, they exhibited no ERG however GIRD; a loss of total GH rotational ROM; scapula downward rotation from rest to 90° elevation; weak SA, GHIR and GHER; PSC stiffness and PML inflexibility were noted.

Dominant shoulder GIRD has been associated with PSC inflexibility,[98,100] loss of total GH rotational ROM[94] and poor shoulder strength in baseball pitchers. This study found a similar trend for GIRD in cricketers. Although GHIR and GHER strength in these cricketers is lower than that reported for baseball pitchers,[40] the GHER:GHIR ratio falls within the normal.[154] Thus, cricketers do not necessarily have an imbalance between GHIR and GHER, but rather global muscle weakness, when compared to their overhead throwing counterparts.[153] However, it is interesting to note that this cohort of cricketers did not demonstrate the concomitant ERG,[100] increased upward scapula rotation at 60°, 90° and 120° GH elevation[100] or reduced AHD measurement,[117] observed when GIRD and PSC inflexibility occur in baseball pitching shoulders.

The GH rotational asymmetries of ERG and GIRD noted in baseball pitchers, are known to be attenuated by adaptive humeral retroversion;[9] a structural anomaly undetected in cricketers.[75] Thus, it appears that young developing cricketers may not achieve the throwing load required to obtain the adaptive humeral retroversion associated with ERG, as this skill is regarded as less essential than batting and bowling by junior cricket coaches.[36] This may explain the lack of ERG and poor GHIR and GHER strength which ultimately contributes to the loss of total GH rotational ROM, demonstrated by the mature cricketers in this study.

Further, this cohort of cricketers presented with consistently downwardly rotated scapulae from rest to 90° GH elevation. The lack of association between PSC stiffness and scapula upward rotation previously observed in baseball pitchers,[100] may occur due to numerous muscular imbalances. In this study, cricketers demonstrated greater lower trapezius (LT), yet weaker serratus anterior (SA) strength when compared to known data for baseball pitchers. Scapula upward rotation requires the synergistic activity of primarily the middle[157] and lower trapezius[90,157] muscles, and secondarily, the SA.[89,90,157] However, the efficacy of the SA as a scapula upward rotator, may be limited in the presence of scapula anterior tilt as it is predominantly responsible for scapula posterior tilt.[89,90,157] Scapula anterior tilting occurs as a result of PM inflexibility.[89,90] The PML in this study was similar to those reported in tennis players, but shorter than the average for the general population.[158]

Consequently, this cohort of cricketers may not have sufficient SA strength to counteract the scapula anterior tilt created by PM inflexibility. In addition, the slightly greater LT strength demonstrated in this study's cricketers, may be insufficient to produce scapula upward rotation in the absence of synergistic SA activity. A resultant scapula position of downward rotation and anterior tilt may thus occur. Subsequently, this scapula position increases the risk for shoulder impingement as the rotator cuff tendons are approximated towards the coracoacromial arch/glenoid lip and excessive anterior or superior humeral head migration occurs.[89,90]

The maintenance of the AHD in this study is another unexpected finding, indicating that the subacromial space is preserved, despite a thicker supraspinatus tendon. Similar findings have been reported in volleyball players[116] where a large AHD was associated with a thicker supraspinatus tendon and greater GH external rotation strength. Conversely, this study demonstrated general weakness of the GHER and GHIR in cricketers that may have occurred as a result of anterior humeral head translation[86,89] or potential internal (glenoid) impingement[16,142] which would inhibit the supra- and infraspinatus muscles.

The findings of this study suggest that the dominant throwing shoulder of cricketers is atypical to that of other overhead throwers, however numerous variables indicate that cricketers are particularly vulnerable to shoulder pain and injury risk. This is further highlighted by the number of uninjured cricketers reporting symptoms with the pain provocation tests, indicating the possibility that a symptomatic shoulder which does not influence performance, is not reported as an injury by cricketers. Clarsen et al (2013)[159] have found that many elite athletes demonstrate this phenomenon of pain without reporting an "injury". Consequently, shoulder injuries in cricketers may still be under-reported; and early diagnosis and treatment is essential to reduce the chronicity and severity of shoulder injuries in this overhead throwing population.

Notably, the influence of these musculoskeletal variables on shoulder function is emphasised by the low mean KJOC scores noted in this study at the start of the season, irrespective of injury. The low KJOC scores may further be attenuated by the deficit in non-dominant hip external rotation ROM and weakness in the dominant hip GM demonstrated by these cricketers, as these biomechanical deficiencies are known to increase the load on the shoulder and negatively influence the performance of overhead throwing in baseball pitchers.[18-20] Further, the potential association between low pre-season KJOC scores and a deficit (≤ 22.75°) in dominant hip internal rotation ROM was shown in cricketers with a history of previous shoulder injury. Extant research has found that dominant hip internal rotation ROM ≤ 30° reduces the risk for trunk, back and lower limb injuries in fast bowlers.[66]

Traditionally, these specialists are positioned in the outer ring when fielding,[3,31,32] requiring overhead throws over a distance of approximately 30m,[38] placing them at risk for shoulder injury due to workload.[2] Consequently, it is suggested that the optimal range of dominant hip internal rotation to prevent shoulder, back, trunk and lower limb injuries in cricketers, may lie between 25°-30°. Lastly, the importance of including the entire kinetic chain in musculoskeletal screening protocols and the assessment of performance parameters is highlighted.

4.5.2 The Musculoskeletal Screening Variables Predictive of Shoulder Injury

The secondary outcome of this study was that dominant SsT and non-dominant shoulder PML predicted dominant shoulder injury. The increase in dominant SsT is thought to occur as a result of repetitive overhead throwing load,[3,31,32] in the absence of sufficient GHER strength.[116] Previous researchers have found that a thicker SsT is associated with a larger AHD, increased GHER strength and a higher GHER:GHIR strength ratio in volleyball players.[116] These cricketers demonstrated a thicker SsT and an AHD on the upper spectrum of the normal, weakness of the GHER and a lower GHER:GHIR strength ratio. This may indicate that the SsT becomes overloaded as it attempts to resist the superior humeral head migration known to occur with deltoid contraction, as the dominant arm cocks in preparation to throw overhead.[160] Thus, a resultant hypertrophy of the SsT may occur with repetitive throwing, similar to that observed in swimmers post-training.[161] Further, this study observed that dominant shoulder SsT thickness ≥5.85mm predicts shoulder injury in cricketers, which is a substantially lower cut-off than that reported to increase the risk of shoulder impingement in volleyball players.[116] This may have occurred as these cricketers did not demonstrate the associated increase in AHD. Lastly, the clinical relevance of SsT thickness as a predictor of shoulder injury in this study is shown to be minimal as the RoC curves demonstrate large measurement variability (4.3-6.7mm). Further research is indicated to fully understand the significance of this finding.

Non-dominant shoulder PML inflexibility will result in scapula anterior tilt, consequently impeding clavicular elevation, retraction and posterior rotation, reducing the range of scapula upward rotation required for GH elevation >60°.[89,90,102] Further, scapula upward rotation has been positively correlated with upper thoracic rotation ROM.[102,162,163] Although this measurement was not included in this study, these cricketers did demonstrate a delay in non-dominant upward scapula rotation from rest to 90°, indicating potential rotational stiffness in the thoracic spine. Consequently, when throwing overhead, cricketers will attempt to position the dominant arm behind the body in greater GH abduction and external rotation in the preparatory and stride phases to compensate for the lack of thoracic rotation.[17,20] A resultant increase in dominant shoulder GH compression occurs[17,20] highlighting the susceptibility of the supraspinatus tendon to irritation in the subacromial space.[89,90]

4.5.3 Value of Pre-season Screening

Numerous variables associated with shoulder injury in overhead sport were tested as part of a comprehensive pre-season shoulder screening protocol suggested for cricketers. Importantly, only 2 of 17 screening tests were shown to be predictive of seasonal shoulder injury in cricketers. In addition, these tests were shown to have either a poor (AUC > 0.60), or fair (AUC > 0.70) ability to distinguish between cricketers who did and didn't sustain an injury. However, the poor association between musculoskeletal screening tests and injury found in this study may have occurred as this entire cohort of cricketers appear to be at higher risk for shoulder injury. Despite the paucity of evidence supporting the use of pre-season screening for injury risk, its value cannot be ignored. Pre-season screening has the potential to highlight and educate clinicians and athletes on specific intrinsic deficits which may increase injury potential. In addition, individualised target-based interventions can be developed, with the long-term aim of enhancing performance through a reduction in injury risk.

4.5.4 Methodological Considerations and Future Directions

This study was conducted over a single season and longer documentation should be considered in the future. However, this was a well-controlled trial as all screening tests were performed by the same author (MD), minimising potential measurement error; and injury data were captured by the respective squad medical personal at the time of injury, thus reducing the reliance on self-report measures. As a saturation sample was utilised in this study, a multi-centre study of cricketers of similar level of play, is suggested to improve statistical power and allow for player speciality/position comparisons with risks factors for injury.

Future research in the development of shoulder specific screening tools, using different measurement techniques, is essential to identify novel injury risk factors and cut-off values. The influence of modifiable shoulder injury risk factors on performance measures in cricket, should be investigated in the development of injury prevention programmes. In addition, studies are suggested that explore the effectiveness of injury prevention programmes on modifiable shoulder injury risk factors in cricket.

4.6 CONCLUSION

In conclusion, a cricketer's shoulder does not demonstrate the characteristics associated with the classic *"thrower's paradox"* and may increase a cricketer's risk of developing shoulder impingement. Although most pre-season screening variables in this cohort were not associated with seasonal injury, dominant SsT thickness and non-dominant PML predicted injury with a high sensitivity and moderate specificity. Thus continued investigation of these variables in a longitudinal study is warranted. Further, the efficacy of a shoulder specific rehabilitation protocol on injury prevention and throwing performance in cricketers should be explored.

Acknowledgements

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Conflicts of Interest

No conflicts of interest for any author.

Summary box

- Cricketer's shoulders are atypical of the classic *"thrower's paradox"*, increasing their vulnerability to injury
- Cricketers present with a loss in total GH rotational ROM and GIRD in the absence of ERG; and global weakness of the rotator cuff and scapula stabiliser muscles
- Dominant supraspinatus tendon thickness and non-dominant pectoralis minor length can predict in-season dominant shoulder injury.
- Shoulder, trunk, back and lower limb injuries may be reduced by obtaining 25-30° of dominant hip internal rotation ROM

Supplementary Table 4.1: A summary of testing sequence, protocols and reliability for all measurements conducted in this study.

Type of Measurement	Test Performed	Testing position	Reference of Protocol Utilised	Instrument used (if applicable)	Intra-rater Reliability	Sequence of testing
Shoulder function questionnaire	-	Self-administered questionnaire	Alberta et al (2010)[131]	Kerlan-Jobe Orthopaedic Clinic Shoulder and Elbow Score (KJOC score)	ICC = 0.88[131]	1
Ultrasonography	Acromiohumeral distance	Sitting, with arm by side and elbow bent to 90° allowing hand to rest comfortably on participant's lap	McCreesh et al (2015)[126]	Diagnostic Ultrasound	ICC = 0.92[126]	2
	Supraspinatus tendon thickness	Sitting with arm by side, elbow bent to 90° and palm placed on iliac crest so that elbow points posteriorly.			ICC = 0.93[126]	
Pain Provocation	Hawkin's/Kennedy	Sitting with tested arm draped over examiner's arm. Examiner stabilises scapula and performs passive GH internal rotation with the participant's arm positioned in 90° GH abduction and 90° GH flexion	Cools et al (2008)[76]	Yes/No for presence of pain	κ=1[164]	3
	Jobe Test	Sitting with both arms positioned at 90° GH elevation, in scapula plane and full GH internal rotation (empty can position). The examiner applies downward force resisting further GH flexion, to both of the participant's arms simultaneously.			κ=1[164]	
	Full Can	As for Jobe's test however both arms are now positioned in 90° GH external rotation (full can position).			Interpreted in conjunction with above tests[165]	
Isometric Strength*	Upper Trapezius	Sitting with arm by side in neutral GH rotation	Hislop et al (1995)[166]	HHD	ICC = 0.79 – 0.96[167]	4
	Serratus Anterior	Supine with 90° GH flexion and full elbow extension	Donatelli et al (2000)[128]			12
	Lower Trapezius	Prone with 145° GH abduction and full external rotation (thumbs up position)				16
	GH External Rotators	Sitting in 90° GH abduction, 90° GH external rotation and 90° elbow flexion	Hayes et al (2002)[168]		ICC = 0.78 - 0.98[168]	5
	GH Internal Rotators				ICC = 0.64 – 0.96[168]	6
	Gluteus Medius	Side lie with lower leg's hip and knee flexed to 30° and upper leg passively positioned in 10° hip abduction and neutral rotation, with full knee extension.	Wilder et al (2009)[169]		ICC = 0.90[169]	15

ROM	Upward scapula rotation	Standing with scapula upward rotation measured at rest, 45°, 90° and 135° GH abduction, in the scapula plane.	Johnston et al (2001)[170], modified by Watson et al (2005)[171]	Inclinometer	ICC = 0.89 – 0.96[170]	7
	GH external rotation (passive)	Supine, with arm positioned in 90° GH abduction, 90° elbow flexion, neutral forearm rotation and wrist in neutral. A towel roll is placed under the upper arm to ensure horizontal positioning.	Kolber et al(2012)[172]		ICC = 0.89 – 0.99[173]	10
	GH internal rotation (passive)					11
	Hip external rotation (passive)	Supine, with hip in neutral flexion/extension and rotation while knee is flexed to 90°.(15,16)	Gabbe et al (2004)[174]		ICC = 0.96[175]	8
	Hip internal rotation (passive)				ICC = 0.93[175]	9
Flexibility	Pectoralis Minor	Supine with arms placed next to torso in neutral GH rotation and full elbow extension	Borstad (2008)[158] and modified by Cools et al (2010)[113]	Calliper	ICC = 0.83 – 0.87[158]	13
	Posterior Shoulder Complex	Supine with 90° GH flexion and 90° elbow flexion. Scapula is stabilised in retraction by the examiner.	Laudner et al (2006)[99]	Inclinometer	ICC = 0.93[99]	14

* The participants were familiarized with the isometric muscle strength testing following completion of the shoulder function questionnaire. Each participant was required to perform three repetitions at 70% of maximum voluntary contraction for each muscle tested, prior to continuing with the shoulder screening protocol.

Supplementary Table 4.2: Sample size determination of outcome measures utilised in this study, based on previous research

Outcome Measure	Smallest Meaningful Difference	Effect Size (d)	Std Dev	Sample Size (Total)
Shoulder pain[32]	10.1	1.2	8	25
Scapula upward rotation[32,86,113]	2°	0.7	3°	65
GIRD[7]	4°	0.8	5°	49
Isometric muscle strength of scapula stabilisers and GH rotators[113,167]	2	0.7	3	65
Pectoralis Minor Length[113]	1.2cm	1.0	1.2cm	30
Posterior Shoulder Tightness[92]	9.6°	1.2	8°	25

PART 2

CHAPTER 5 – OVERHEAD THROWING IN CRICKETERS: A BIOMECHANICAL DESCRIPTION AND PLAYING LEVEL CONSIDERATIONS

This Chapter is under review as an original article:

Dutton, M., Gray, J., Prins, D., Divekar, N., Tam, N. (submitted 10 April 2019) Overhead throwing in cricketers: A biomechanical description and playing level considerations. *Journal of Sports Sciences.*

For the purposes of this thesis, figures and tables as well as their captions have been placed in the appropriate places within the text of the article and general formatting is aligned with the requirements of the Doctoral Degrees Board, University of Cape Town.

A detailed copy of the methodology used for the biomechanical analysis of overhead throwing described in this Chapter, as well as Chapters 6 and 7, can be found in Appendix III.

5.1 ABSTRACT

Objectives: To describe the biomechanics of stationary overhead throwing in cricket, relative to baseball, and compare the differences between elite and amateur cricketers.

Methods: Stationary overhead throwing was assessed in 21 South African cricketers. Kinematics and ground reaction forces were collected during these throwing trials. Inverse dynamics was used to calculate joint kinetics. Inter-subject variability was calculated using the coefficient of variance. One-dimensional statistical parametric mapping ANOVA was conducted to assess differences between the kinematic waveforms for elite and amateur cricketers ($p<0.05$).

Results: 15 cricketers (elite: n=8; amateur: n=7) participated in this study, 22.0 ± 3.4 years. The basic parameters of a cricketer's throwing action are described. Substantial inter-subject variability was noted for all variables, except lumbopelvic movement, irrespective of playing level. Cricketers presented with 74.9 ± 27.3° glenohumeral external rotation and 94.8 ± 23.7° elbow flexion, at maximum external rotation (MER). Amateur cricketers displayed decreased elbow flexion range of motion between 2-14% of the throwing cycle ($F=9.365$; $p=0.01$); greater shoulder (121.0 vs 85.9N; $F=0.36$, $p=0.021$) and elbow compression (105.6 vs 72.8N; $F=0.007$, $p=0.043$), and superior shoulder force (203.1 vs 115.5N; $F=2.43$, $p=0.022$) at MER, when compared to elite cricketers.

Conclusion: Cricketers display a similar trend to baseball pitchers when throwing overhead from a stationary position. The "preparatory arc" utilised is different to the wind-up noted for baseball. The forces exerted on the shoulder and elbow, in amateur cricketers specifically, are significantly greater and may indicate the potential risk for injury at maximum external rotation.

5.2 INTRODUCTION

The development of cricket disciplines towards shorter, explosive formats of the game such as limited over one-day and T20 matches, have highlighted the importance of fielding performance for run restriction.[1] The ability of fielders to throw with both speed and accuracy; and catch a ball in flight, are essential skills to limit runs scored or dismiss the batsmen.[2]

Currently, our understanding of throwing is based on overhead baseball pitching.[10,18,19] This motion is thought to be comparable to the overhead throw employed by cricketers,[35] however quantifiable differences in throwing velocity,[1,109,111], accuracy[111] and biomechanics[35,37,109] have been identified. Specifically, cricketers have less elbow flexion during the stride phase of throwing resulting in a lower vertical release trajectory of the ball.[37,109] Subsequently, a 'preparatory arc' of the upper limb has been described during cricket throwing, rather than a baseball pitcher's wind-up.[10,18,19] Unfortunately, little else is known about basic throwing biomechanics in cricket.

Currently, only three studies have attempted to describe the overhead throwing technique utilised by cricketers, when fielding. These studies have focused on age-related differences in overhead throwing performance[37] and throwing kinematics from wind-up to ball release over differing fielding scenarios.[1,39] In addition, a speed-accuracy trade-off is evident, indicating that biomechanical adaptations potentially contribute to a cricketer's ability to throw accurately over distance, albeit with compromised speed.[36] Further research is warranted as studies were limited in sample size and repeated trials. The applicability of the findings to players of different levels and individual differences in throwing biomechanics are not clear. The forces acting about the shoulder joint at arm cocking and ball release have not been described as previous studies used a two-dimensional (2D) image-based motion analysis.[176] Moreover, the description from point of ball release to arm deceleration has yet to be described in cricket.

An understanding of the forces experienced by the upper extremity at late arm cocking, the point of ball release and arm deceleration are required to determine the critical moments in performance of overhead throws by cricketers. Therefore, the aim of this study was to fully describe the kinematics and kinetics of the overhead throw (from cocking to follow-through) in cricketers in comparison to current baseball pitching literature. In addition, individual and group differences in the evaluated parameters of the overhead throw between elite and amateur cricketers were examined.

5.3 METHODS

5.3.1 Participants

Twenty-one healthy male cricketers representing a national, elite or amateur franchise team were invited to participate in this study. Participants were excluded from this study if they presented with cervical and neurological symptoms, a history of shoulder surgery and/or traumatic shoulder injury, as well as current shoulder pain. To ensure optimal conditioning of the dominant shoulder when throwing, cricketers were tested within a one-month period in the middle of the domestic cricket season. Eligible participants provided written informed consent. The study was granted ethical approval by the institutional human research ethics committee.

Prior to biomechanical testing, anthropometric measurements of height, mass, leg length and ankle, knee, elbow and third metacarpophalangeal joints widths were recorded. Throwing trials were conducted in a biomechanical laboratory with ample space to throw.

5.3.2 Instrumentation

Three-dimensional marker trajectories were captured using an eight camera Vicon MX motion analysis system (Oxford Metrics Ltd., Oxford, UK), sampling at 500 Hz. Ground reaction force data were collected using two 900 x 600 mm force platforms (AMTI Inc., Watertown, MA, USA), sampling at 2000 Hz. Retro-reflective markers were attached according to a custom upper body[61] and modified Helen-Hayes lower body[177] marker sets.

5.3.3 Testing protocol

Participants were then required to perform a standard fielding warm-up, including a series of dynamic stretches to the lower back, upper and lower limbs; and four overhead throws for familiarisation purposes, before commencing with the throwing trial.

For each throwing trial participants were positioned with both feet towards the back of the rear force platform to allow dominant foot placement on the front force platform during the throw. Participants were requested to perform overhead throws as fast as possible, to mimic a run-out scenario. Throws were directed towards a set of stumps, surrounded by a one square metre target, positioned 20-m away. Synchronised collection of marker motion and force platform data were obtained for each throw. Six overhead stationary throwing trials were performed. A successful trial was one in which each foot contacted the respective force platforms, where all the markers were in view of the cameras and the ball hit either the target or stumps.

5.3.4 Data Analysis

Marker trajectory and force plate data were filtered using a low-pass fourth-order Butterworth filter with cut-off frequency at 6 and 100 Hz, respectively. The lower body PlugInGait and custom upper-body model were applied to marker trajectories. Three-dimensional joint angles and net resultant joint forces were calculated using a Newton-Euler inverse dynamics approach. All joint angles followed the Euler XYZ rotation sequence, except the shoulder which followed a YXY rotation sequence; and were described according to the joint co-ordinate systems recommended by the ISB.[178-180] Three-dimensional joint forces were expressed in newton (N). Shoulder force was determined as force applied by the trunk to the upper arm; whereas elbow force was calculated as force applied by the upper arm to the forearm.[4] The overhead throw was analysed from neutral shoulder rotation to the reversal of shoulder rotation (internal to external rotation) following ball release and dominant arm deceleration. Specific phases of the throwing cycle are described as follows:

i. Preparatory phase: From neutral shoulder rotation to the point of maximum shoulder external rotation (MER)
ii. Arm acceleration: From MER to the point of ball release (BR)
iii. Ball release (BR): Point at which the ball is released from the dominant hand, directed towards the target
iv. Arm deceleration: From BR to maximum shoulder internal rotation (MIR), prior to the reversal of shoulder rotation

Data for each participant's dominant throwing limb were averaged over three successful good-quality trials. Joints of interest included shoulder, elbow, thoraco-lumbar, lumbo-pelvic and hip joint angles. Kinematic and kinetic data are represented as wave-forms that changed continuously throughout the overhead throw and were defined with 101 data points, one for each percentage of the overhead throw.

5.3.5 Statistical Analysis

Data were screened for normality of distribution using Shapiro-Wilk's test. Movement variability of each outcome variable was determined by calculating the within-cricketer error of each group to produce the coefficient of variance (CV), expressed as a percentage of the mean. The within-cricketer CV of the two groups were compared by determining the CV ratio. Movement variability was regarded as substantial if the groups differed by >1.15 or <0.85.[181] One-dimensional statistical parametric mapping (1DSPM) one-way ANOVA (SPM[f]) was used to determine differences between elite and amateur cricketers' waveform variables.

All 1DSPM analyses were implemented using the open source 1DsSPM code (v.M0.4, www.spm1d.org) in Matlab (R2017b, Mathworks Inc., Natick, MA, USA). Significance was set at $p<0.05$.

5.4 RESULTS

5.4.1 Participants

Of the 21 cricketers recruited for the study, the data obtained from six participants were excluded due to poor quality trials, resulting in 15 cricketers included for analysis with a mean age of 22.0 ± 3.4 years, height of 1.9 ± 0.8 metres and mass of 76.9 ± 10.5 kg.

5.4.2 Description of overhead throwing from a stationary position

The overhead throwing cycle was completed in 0.73 ± 0.18 s (100% of the throwing cycle) that comprised of 0.32s-preparation (45%), 0.07s-arm acceleration (9%) and 0.17s (23%) for both arm deceleration and follow-through, respectively (Table 5.1). At MER, the majority of cricketers were positioned with the dominant hip in neutral flexion/extension, slight abduction and external rotation. Minimal lumbo-pelvic movement occurred, but thoraco-lumbar extension and rotation towards the dominant arm was evident. The shoulder achieved MER equivalent to 74.9 ± 27.3°, between 91.2 ± 9.3° of shoulder elevation, while the elbow was flexed to 94.8 ± 23.7°. The forces acting about the shoulder were 7.2 ± 14.1N posteriorly, 156.4 ± 77.3N superiorly and 102.2 ± 30.8N compression. The greatest force experienced at the elbow was 88.1 ± 32.1N compression. Figure 5.1 summarises the shoulder and elbow kinematics, as well as the shoulder kinetics.

The point of BR was characterised by five degrees more shoulder elevation and the initiation of both GH internal rotation (11.9°) and elbow extension (21.5°), when compared to the position attained by cricketers at MER. In addition, the initiation of thoraco-lumbar flexion and de-rotation towards the non-dominant side, as well as the commencement of dominant hip flexion were noted. Further, all the forces acting about the shoulder and elbow, with the exception of medial force, were vastly reduced in relation to MER. Medial elbow force increased by 2.7 times, from 19.0 ± 29.1N at MER, to 52.7 ± 32.8N at BR.

At MIR, cricketers were positioned in low range shoulder elevation (less than 65°), approximately 45° elbow flexion, neutral thoraco-lumbar flexion/extension but rotation towards the non-dominant side, as well as the greatest range of lumbo-pelvic flexion, and dominant hip flexion and external rotation. The forces acting about the shoulder were 61.4 ± 24.1N distraction, 62.2 ± 35.8N posterior and a similar inferior force to that described at the point of BR.

5.4.3 Kinematics and kinetics of critical points in cricket throwing

Only a single waveform difference between elite and amateur cricketers was found (Figure 5.2). Amateur cricketers demonstrated lower elbow flexion angles when compared to elite cricketers between 2-14% of the throwing cycle ($F=9.365$; $p=0.01$). No kinematic differences were found in the shoulder, thoraco-lumbar, lumbo-pelvic and hip joints.

Lastly, differences between elite and amateur cricketers were found in shoulder and elbow forces at MER (Table 5.2). At MER, amateur cricketers exhibited greater shoulder ($F=0.36$; $p=0.021$) and elbow compression ($F=0.007$; $p=0.043$), as well as greater superior shoulder force ($F=2.43$; $p=0.022$) than the elite cricketers.

5.4.4 Movement variability

At MER, the elite group displayed greater movement variability than the amateur group for shoulder elevation and rotation, elbow flexion, thoraco-lumbar rotation, hip flexion and rotation (Table 5.3). Conversely, lower movement variability in elbow valgus-varus and thoraco-lumbar flexion-extension was found in the elite group than the amateur group.

A similar trend in movement variability was noted at BR, for shoulder elevation and rotation, elbow valgus-varus and thoraco-lumbar flexion-extension. In addition, in comparison with the amateur group, the elite group displayed less variance in thoraco-lumbar and hip rotation but greater hip ab/adduction variance.

Finally, at MIR the elite group displayed lower movement variability in shoulder elevation, all elbow variables, thoraco-lumbar and hip rotation, compared to the amateur group. Consequently, the elite group only displayed greater movement variability than the amateur group, for hip flexion/extension and ab/adduction.

Table 5.1: Total throwing cycle and joint angles at MER, point of BR and MIR, for this cohort of cricketers, compared to the normative values for baseball pitchers

	Normative Values for Baseball Pitchers	**Cricket Cohort**		
		All (n=15)	**Elite (n=8)**	**Amateur (n=7)**
Total throwing cycle (s)	0.145[18]*	0.73 ± 0.18	0.71 ± 0.21	0.75 ± 0.15
Shoulder (°)				
Maximum External Rotation				
Elevation (+)	94 ± 21[4]	91.2 ± 9.3	89.2 ± 10.8	93.4 ± 7.4
Internal (+)/External (-) rotation	-175 ± 11[63]	-74.9 ± 27.3	-73.6 ± 30.3	-76.4 ± 25.8
Ball Release				
Elevation (+)	93 ± 10[4]	96.1 ± 6.4	94.1 ± 6.2	98.3 ± 6.2
Internal (+)/External (-) rotation	-64 ± 35[4]	-63.0 ± 42.4	-58.8 ± 48.5	-67.7 ± 37.4
Maximum Internal Rotation				
Elevation (+)	-	63.9 ± 16.9	62.2 ± 11.1	65.9 ± 22.7
Internal (+)/External (-) rotation	-	-15.0 ± 20.6	-6.2 ± 20.3	-25.1 ± 17.0
Elbow (°)				
Maximum External Rotation				
Flexion (+)/Extension (-)	98 ± 15[63]	94.8 ± 23.7	92.4 ± 26.3	97.5 ± 22.0
Valgus (+)/Varus (-)	-	-8.5 ± 6.4	-10.7 ± 5.5	-5.9 ± 6.8
Ball Release				
Flexion (+)/Extension (-)	23 ± 5[63]	73.3 ± 26.9	68.8 ± 26.7	78.5 ± 28.2
Valgus (+)/Varus (-)	-	-10.8 ± 5.4	-13.0 ± 5.0	-8.2 ± 4.9
Maximum Internal Rotation				
Flexion (+)/Extension (-)	-	45.7 ± 13.4	46.8 ± 9.3	44.4 ± 17.7
Valgus (+)/Varus (-)	-	-1.1 ± 4.7	-1.3 ± 4.6	-0.9 ± 5.3

*Throwing cycle measured from foot strike to ball release

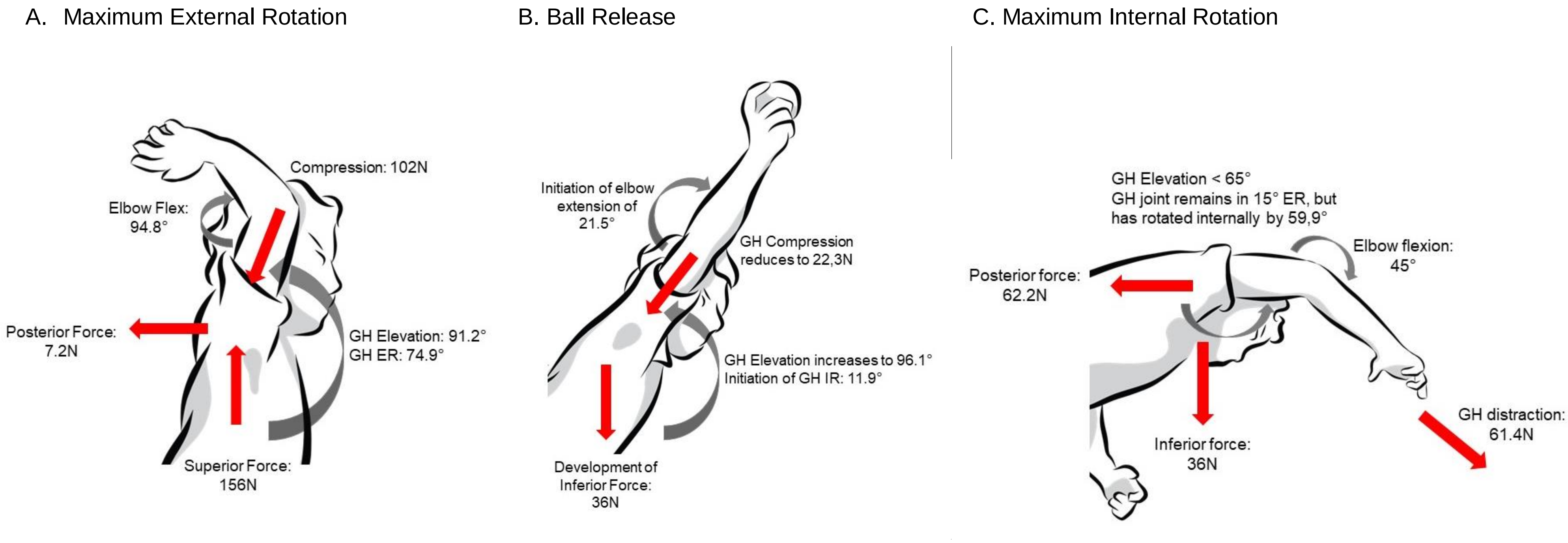

Figure 5.1*:* The kinematics (grey arrows) and kinetics (red arrows) of the shoulder joint presented at A. Maximum External Rotation, B. Ball Release and C. Maximum Internal Rotation, when a cricketer throws from a stationary position.

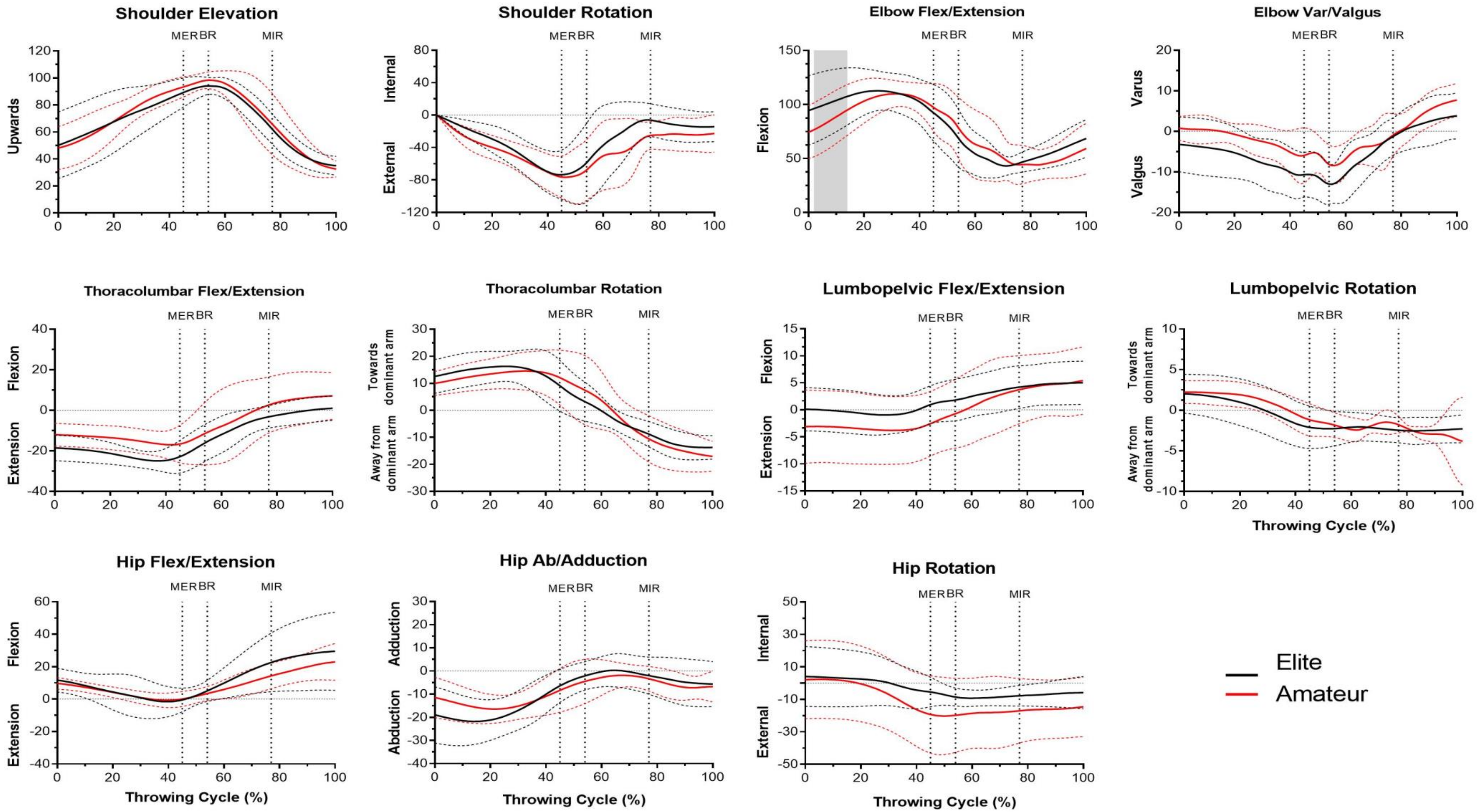

Figure 5.2: Kinematic data over an entire throwing cycle; mean ± 1 standard deviation for elite (black) and amateur (red) cricketers (n=15) with significant differences between playing levels ($p < 0.05$, grey shaded band).

Table 5.2: Shoulder and elbow forces at critical points in throwing cycle for this cohort of cricketers compared to the normative values for baseball pitchers.

	Normative Values for Baseball Pitchers[4]	Cricket Cohort		
		All (n=15)	Elite (n=8)	Amateur (n=7)
Shoulder				
Maximum External Rotation				
Distraction (+)/Compression (-)	-480 ± 130	-102.2 ± 30.8	-85.9 ± 27.1*	-121 ± 24.3*
Superior (+)/Inferior (-)	250 ± 80	156.4 ± 77.3	115.5 ± 75.4*	203.14 ± 50.1*
Anterior (+)/Posterior(-)	380 ± 90	-7.2 ± 14.1	-4.8 ± 17.2	-9.9 ± 10.3
Ball Release				
Distraction (+)/Compression (-)	-1 090 ± 110	-22.3 ± 26.4	-19.4 ± 25.5	-25.8 ± 29.5
Superior (+)/Inferior (-)	240 ± 80	119.8 ± 64.5	102.0 ± 60.2	140.65 ± 68.2
Anterior (+)/Posterior(-)	80 ± 180	0.6 ± 24.6	7.7 ± 12.7	-7.6 ± 33.3
Maximum Internal Rotation				
Distraction (+)/Compression (-)	1 100 ± 100	61.4 ± 24.1	55.6 ±13.1	68.1 ± 32.5
Superior (+)/Inferior (-)	-310 ± 80	119.7 ± 35.4	120.7 ± 38.0	118.4 ± 34.8
Anterior (+)/Posterior(-)	-400 ± 90	-62.2 ± 35.8	-57.0 ± 26.5	-68.1 ± 45.8
Elbow				
Maximum External Rotation				
Compression (+)/Distraction (-)	270 ± 120	88.1 ± 32.1	72.8 ± 27.9*	105.6 ± 28.7*
Superior (+)/Inferior (-)	-	27.8 ± 13.5	31.4 ± 13.8	23.7 ± 12.8
Medial (+)/Lateral (-)	300 ± 60	19.0 ± 29.1	9.9 ± 29.7	29.4 ± 26.7
Ball Release				
Compression (+)/Distraction (-)	900 ± 100	22.2 ± 26.8	12.7 ± 22.0	33.4 ± 29.5
Superior (+)/Inferior (-)	-	39.5 ± 22.3	35.2 ± 23.3	44.6 ± 22.0
Medial (+)/Lateral (-)	-	52.7 ± 32.8	42.8 ± 29.4	64.2 ± 35.3

* Significant difference $p < 0.05$

Table 5.3: Between-group differences in movement variability values displayed at critical points in the throwing cycle for elite and amateur cricketers.

Joint Variable	At MER					At BR					At MIR				
	Elite		Amateur		CV Ratio	Elite		Amateur		CV Ratio	Elite		Amateur		CV Ratio
	Error	CV%	Error	CV%		Error	CV%	Error	CV%		Error	CV%	Error	CV%	
Shoulder															
Elevation	3.8	12	2.8	8	1.50[a]	2.2	7	2.3	6	1.17[a]	3.9	18	8.6	34	0.53[b]
Ext-internal rotation	10.7	41	9.8	34	1.21[a]	17.2	65	14.1	55	1.18[a]	7.2	50	6.4	46	1.09
Elbow															
Flex-Extension	9.3	28	8.3	23	1.22[a]	9.4	39	10.7	36	1.08	3.3	20	6.7	39	0.51[b]
Var-Valgus	2.0	44	2.6	89	0.50[b]	1.8	38	1.8	59	0.64[b]	1.6	56	2.0	98	0.57[b]
Thoracolumbar															
Flex-Extension	2.8	35	3.5	55	0.64[b]	3.2	56	5.8	84	0.67[b]	2.0	80	5.2	71	1.13
Rotation towards/away from dominant arm	3.3	89	3.8	74	1.20[a]	2.6	67	4.8	133	0.50[b]	1.7	53	3.2	81	0.65[b]
Lumbopelvic															
Flex-Extension	1.2	84	2.3	94	0.89	1.4	78	2.4	88	0.89	1.4	82	3.4	90	0.91
Rotation towards/away from dominant arm	0.9	75	0.7	73	1.03	0.8	94	0.6	83	1.13	0.5	63	0.4	56	1.13
Hip															
Flex-Extension	2.6	91	1.7	62	1.47[a]	2.3	90	1.6	89	1.01	6.4	80	3.0	55	1.45[a]
Abd-Adduction	2.5	61	3.6	69	0.88	2.2	79	3.6	64	1.23[a]	2.8	125	2.0	80	1.56[a]
Ext-Internal Rotation	3.2	46	9.0	97	0.47[b]	1.9	46	8.6	92	0.50[b]	2.2	81	7.5	117	0.69[b]

Within subject variance (Error), within subject coefficient of variance percentage (CV%).

[a]Indicates substantial difference in within-subject CV with a CV ratio > 1.15 and the Amateur group displaying lower variability.

[b]Indicates substantial difference in within-subject CV with a CV ratio < 0.85 and the Elite group displaying lower variability.

5.5 DISCUSSION

This study found that the throwing cycle of cricketers differs to previous reported overhead throwing cricket studies.[1,39] This is probably due to the definition of sub-phases during the throwing task. The phases in this study are described according to the degree of shoulder rotation, rather than the sequence of back foot strike to ball release,[1,39] as the throwing action was performed from a stationary position, with the back foot planted at the start. Consequently, total throw time is expressed as a percentage based on shoulder rotation, as opposed to the maximum segment endpoint velocity used previously.[1,39]

The phases of stationary overhead throwing, shoulder joint kinetics, variability in throwing technique, as well as the kinematic and kinetic differences between elite and amateur cricketers, are discussed below.

5.5.1 Description of Stationary Overhead Throwing in Cricketers

i. Preparation Phase and Maximum External Rotation

The range of motion reported for shoulder elevation, is similar to that found in baseball[18] yet indicates that cricketers tend toward a side-arm shoulder position,[25] despite instruction to throw overhead. The side-arm technique has been found to be inferior to the overhead throwing technique when considering both velocity and accuracy, in cricketers.[38] The lower shoulder elevation angle may allow these cricketers to obtain the speed-accuracy trade-off necessary to affect a run-out from a stationary position.

Notably, throwing velocity has been directly associated with MER in baseball pitchers.[10,11] This cohort of cricketers demonstrated substantially lower MER than the 102-143° previously reported in the 2D studies conducted on cricketers when throwing from a 180° approach angle, over 20m.[1,39] While the accuracy of 2D measurement of GH external rotation is questionable, this result highlights the possibility that throwing velocity may be compromised in these cricketers. Consequently, performance may be affected and the potential risk for injury increased, as the kinetic chain may compensate for the lack of MER. Biomechanically, it has been speculated that thoracolumbar extension may increase the potential for shoulder external rotation during submaximal throws over 40m.[1] However, the results of this study were contrary to this where the degree of elbow flexion exceeded previously reported throws over 20 and 40m, with different approach angles,[1] but similar to baseball pitchers.[182] This suggests that cricketers are reliant on elbow flexion, to increase the distance available to accelerate the ball from MER rather than GH external rotation ROM, when throwing from a stationary position.

The forces noted at the shoulder are similar in direction yet substantially lower in magnitude compared to those described in baseball pitchers.[4] When considering the musculoskeletal adaptations to overhead throwing, it is known that the strength of the GH external rotators influences pitching velocity.[11] Although muscular strength was not considered in this study, the rotator cuff (specifically the supraspinatus muscle) in conjunction with the deltoid which are known to produce a trans-articular compressive force across the GH joint in mid-range abduction,[105-107] may be responsible for both the compressive and superior forces noted at the shoulder in this study.

The differences in magnitude of force between these overhead throwing populations may be attributed to lower MER of the cricketers when compared to the values previously noted in baseball.[4] Thus, cricketers would incur less superior humeral translation and subsequently, lower activity in the rotator cuff occurs to provide GH stability.[18,103,104] Instability of the GH joint associated with end ROM, specifically MER, increases the strain exerted on the anterior shoulder[10,18] and potentially increases the risk for impingement of the rotator cuff tendons.[18]

A similar trend for the direction and magnitude of forces acting about the elbow, is described between cricketers and baseball pitchers.[182] The lower elbow compression (56-120N vs 150-350N[182]) and medial force (0-48N vs 240-360N[182]) may be attributed to a longer throwing cycle of cricketers than baseball pitchers.[10,18] Therefore, less elbow force is required to counter the trunk and arm rotational velocity at MER.[10,182] Ultimately, this position remains a critical point in overhead throwing for cricketers.

ii. Arm Acceleration and the Point of Ball Release

The findings of this study are similar to that previously reported for baseball pitchers[18,19] and cricketers throwing from a variety of approach angles;[1,39] highlighting the rapid extension of the elbow over approximately 20°, together with the initiation of GH internal rotation, all of which occurs in only 9% of the total throwing time. Importantly, these cricketers have shown to maintain greater than 90° GH elevation at BR, thereby potentially optimising strength, enhancing ball velocity and reducing the risk for shoulder impingement.[18-20]

Interestingly, at BR, the forces acting about the shoulder and elbow are lower than at MER, in contrast to previously reported values for baseball pitchers, where compressive forces around the shoulder approximately double (MER: 480N, BR: 1 100N), while an inferior shear develops (MER: 0N, BR: 110N).[4] These forces have been shown to provide dynamic GH stability through concentric rotator cuff[18-20] and eccentric biceps brachii strength.[10] Although this study noted that an inferior shear developed between MER and BR, the compressive forces acting about the shoulder decreased over the same period. This highlights the potential lack of concentric rotator cuff and eccentric biceps strength in cricketers.

Therefore, BR may be considered a critical point in overhead throwing for cricketers, due to the risk for potential failure of the dynamic and overload of the passive (ligaments and labrum) GH stabilisers resulting in excessive humeral head translation; rather than excessive forces acting on the shoulder, as described in baseball pitching.[4]

iii. Deceleration Phase

Following BR, a similar pattern of elbow extension and shoulder internal rotation was followed as described in baseball literature.[18,19] Notably, the cricketer's shoulder remains in a degree of external rotation as it does not move beyond neutral rotation. It is known that arm deceleration in baseball is aided by GH horizontal adduction created by thoraco-lumbar flexion and rotation towards the non-dominant side.[18] While the latter movement is demonstrated in this study, no thoraco-lumbar flexion occurs. Instead, these cricketers appear to use lumbo-pelvic flexion to aid arm deceleration. A lack of sufficient thoraco-lumbar flexion during arm deceleration and follow through may increase the load and potential risk for injury to the posterior rotator cuff and superior labrum.[10]

When considering the shoulder forces during arm deceleration, the findings concur with those reported for baseball pitchers however are lower than the posterior and inferior forces noted in the overhead throwing population.[4] The shear magnitude of these forces are considered to be the primary reason that arm deceleration is regarded as a critical point in the throwing cycle of baseball players. However, this may not be true for cricketers when throwing from a stationary position, as cricketers throw with a significantly lower velocity than baseball pitchers.[111] Hence the force required to decelerate the arm should be less in cricketers than baseball pitchers. Consequentially, this phase can only be considered as a critical point in the stationary throwing cycle for cricketers in the absence of sufficient GH external rotator muscle strength,[125] as well as posterior shoulder capsule and GH ligamentous integrity.[4] Future research should consider including a measure of GH external rotator strength, posterior shoulder capsule length and GH ligamentous laxity when assessing the forces exerted on the shoulder in the deceleration phase of throwing in cricket.

5.5.2 Variability in throwing technique

Substantial inter-cricketer variability in the performance of stationary overhead throwing occurs for all the joints (except lumbo-pelvic) measured and in all throwing phases, irrespective of a cricketer's level of participation. This suggests that each cricketer has a unique throwing technique possibly as a result of the musculoskeletal idiosyncrasies inherent to each player. In addition, the lack of sufficient throwing technique training, especially at an early age where the skill of batting and bowling compete for time[36] may be a factor. Further research to understand this throwing variability will assist in determining whether it is desirable.

5.5.3 Biomechanical differences between elite and amateur cricketers

Differences between a cricketer's level of participation were found in the kinematics of the elbow during preparation phase of overhead throwing and the forces acting about the shoulder and elbow at MER. Initially, amateur cricketers display lower elbow flexion, than elite cricketers in the first 14% of the throwing cycle. Maximum elbow flexion is known to be controlled through the eccentric and isometric activity of the triceps which counteracts the centripetal elbow flexion torque and resultant distraction at MER, as a result of the rapidly rotating trunk and shoulder during baseball pitching.[182] Consequently, amateur cricketers may require higher elbow compressive forces to manage the greater elbow flexion range. In addition, the position of the elbow is known to influence the force applied to the shoulder, which may further be attenuated by higher degrees of GH external rotation.[10] Amateur cricketers were found to have both these variances in upper limb ROM possibly explaining the greater shoulder compressive and superior forces, than the elite cricketers.

Thus amateur cricketers perform a slightly longer arc of preparation with a delay in arm acceleration and consequently a slower ball speed may be expected when throwing from a stationary position, as the time to reach MER and BR differed by 0.02 and 0.01 seconds respectively, between elite and amateur cricketers. In addition, the magnitude of forces experienced by amateur cricketers may place them at greater risk of shoulder and elbow injury during throwing tasks, such as fielding and batting throw-downs. While it is evident that amateur cricketers lack a refined throwing technique, the effect of throwing volume, intensity and frequency should also be considered with regards to injury risk.

This study only assessed overhead throwing from a stationary position, in a cohort of cricketers and failed to include performance parameters such as throwing velocity and accuracy. Future studies should consider including cricketers of different playing ability (age-group, junior elite, senior amateur and elite) when assessing the biomechanics of overhead throwing. In addition, the assessment of throwing performance, as well as the influence of approach angles on the musculature of the shoulder when throwing in cricket requires investigation.

5.6 CONCLUSION

When throwing from a stationary position, cricketers demonstrate substantially lower MER, yet similar elbow flexion range compared to baseball pitchers. These biomechanical variances contribute to cricketers experiencing the highest forces acting about the shoulder and elbow at this point in the throwing cycle, indicating the potential risk for injury. This is especially true for amateur players. Notably, these forces are substantially less than those reported in baseball literature. Further research is required to examine the potential relationship between musculoskeletal variables and overhead throwing in the context of both performance and injury risk, in cricketers.

Acknowledgements

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Conflicts of Interest

No conflicts of interest

Summary box

- Cricketers achieve less MER than baseball pitchers, indicating a greater reliance on elbow flexion to throw overhead
- MER is the point at which cricketers experience the greatest shoulder and elbow forces, which are substantially lower than those reported for baseball.
- Movement variability occurs for all kinematic parameters, except lumbo-pelvic movement, during the stationary overhead throwing cycle (irrespective of level of participation)
- MER and the point of ball release could be regarded as critical points in the stationary overhead throwing cycle of cricketers due to the forces exerted on the shoulder and inherent GH instability, respectively.

CHAPTER 6 – DO CRICKETERS EMPLOY DIFFERENT OVERHEAD THROWING BIOMECHANICS FOLLOWING A RUN-UP?

6.1 ABSTRACT

Objectives: To compare the kinematics and kinetics of an overhead throw in cricket when performed from a stationary position and with a run-up (dynamic).

Design: Observational, cohort study

Setting: Institutional biomechanical laboratory

Methods: Fifteen South African cricketers performed six overhead throws, from a stationary position and with a run-up over 15-20 m prior to fielding a ball, respectively. Kinematic data and ground reaction forces were collected throughout the throwing trials. Joint kinetics were calculated using inverse dynamics. An independent t-test or Mann-Whitney U test was used to determine joint kinetic differences between throwing approaches. Differences between the kinematic waveforms for stationary and dynamic throwing approaches were assessed using one-dimensional statistical parametric mapping ANOVA ($p<0.05$).

Results: The shoulder, elbow and thoraco-lumbar joints displayed similar kinematics between the two throwing approaches**.** The dynamic approach displayed increased hip flexion between 0-34% and 57-100% ($F= 6.726$; $p=0.01$) of the throwing cycle; and lumbo-pelvic flexion between 57-65% ($F= 6.823$; $p=0.02$) of the throwing cycle; greater shoulder compression ($F=1.036$; $p=0.02$) and posterior force ($F=1.052$; $p=0.009$) at maximum external rotation; yet less superior shoulder force ($F=1.744$; $p=0.005$) and elbow compression ($F=4.331$; $p=0.03$), superior ($F=1.212$; $p=0.002$) and medial ($F=1.370$; $p=0.03$) elbow forces at BR, when compared to a stationary approach.

Conclusion: When throwing dynamically, greater forces were experienced by the shoulder at MER, indicating a potential increased risk for injury which may be further compounded by the lack of musculoskeletal adaptation. Cricketers maintain similar upper limb kinematics between overhead throwing approaches, emphasising their ability to adjust for different lower limb and trunk kinematics. However, the potential effect of changes in lower limb kinematics on overhead throwing performance is highlighted by the lower upper limb forces experienced at ball release, when throwing dynamically. This highlights the assistance provided by the entire kinetic chain during throwing arm/shoulder deceleration.

6.2 INTRODUCTION

Overhead throwing is an essential skill utilised during cricket fielding to either limit the number of runs scored by a batsman or effect a run-out, to dismiss the batsman.[2] This is achieved by accurately throwing the ball back to the stumps, utilising different approaches.[1,39] A fielder may be required to throw from a stationary position if the ball is hit directly to their position. Alternatively, fielders may approach a throw with a run-up if they are required to run in towards the wicket to collect a ball hit in front of them. Lastly, fielders may need to chase after a ball, turn and throw, if a ball is hit past them.

The few studies which have attempted to describe overhead throwing in cricket from a variety of approach angles have reported a subtle change in sequential arm movement when throwing over distances ≥20 m.[1,39] More specifically, the peak linear velocity of the shoulder occurs at or before that of the hip,[1,39] potentially highlighting a kinetic difference required in maintaining ball velocity and accuracy when throwing over increased distances.[1] This finding is thought to occur as a result of the shorter stride, greater elbow flexion during the preparatory arc of throwing, increased thoraco-lumbar extension and subsequently greater shoulder external rotation at the end of cocking.[1,39] Conversely, when throwing from a stationary position, cricketers have been shown to demonstrate greater elbow flexion and substantially less shoulder external rotation at cocking, than previously reported[1] (Chapter 5). These results contrast those reported for team handball where a comparison of overhead throwing performance from a stationary position to throwing with a run-up demonstrated similar dominant arm kinematics, but differing ball velocity.[183] The latter is thought to be directly associated with the run-up, as it increases pelvic and trunk rotation and shoulder internal rotation angular velocity.[183]

The different methodological approaches and throwing cycle definitions used in the previous cricket studies, make direct comparison challenging and may explain, in part, the contrast in findings for dominant arm kinematics between cricket and handball. In addition, the influence of a run-up when throwing overhead, on shoulder and elbow kinetics has yet to be explored during cricket fielding. Therefore, the aim of this study was to compare the kinematics and kinetics of overhead throwing between stationary and run-up (dynamic) approaches, in cricket fielders.

6.3 METHODS

6.3.1 Participants

Participants were required to represent either a national, elite or amateur franchise team. Fifteen healthy male cricketers who presented with fully functional dominant shoulders and had no cervical or neurological symptoms, history of shoulder surgery and/or traumatic shoulder injury, were invited to participate in this study. All eligible participants provided written informed consent prior to the commencement of the study (Appendix IV).

Anthropometric measurements of height, mass, leg length and ankle, knee, elbow and third metacarpophalangeal joint widths were recorded prior to biomechanical testing (Appendix V). All testing was performed in a single visit at the institution's biomechanics laboratory, as previously described in Chapter 5.

6.3.2 Instrumentation

An eight camera Vicon MX motion analysis system (Oxford Metrics Ltd., Oxford, UK) was used to capture 3D marker trajectories, at 500 Hz. Alongside, synchronised collection of two 900 x 600 mm force platforms (AMTI Inc., Watertown, MA, USA) collected ground reaction force data, at 2000Hz. A custom upper body[61] and modified Helen-Hayes lower body[177] retro-reflective marker set were attached to each participant (Figure 6.1).

6.3.3 Procedures

Overhead throwing biomechanics was tested in a one-month period during the domestic cricket season, to ensure optimal conditioning of the dominant shoulder. Ethical approval for this study was granted by the institutional human research ethics committee (Appendix VI). Dynamic overhead throwing trial analysis commenced following the placement of 73 retro-reflective markers,[61,177] a standard fielding warm-up and the performance of the static throwing trials described in Appendix III. A potential run-out scenario was mimicked during this throwing trial where participants were required to run forward over 15-20 m, field a stationary ball off the ground with their dominant hand and throw overhead as quickly as possible towards a set of stumps positioned 20 m away, surrounded by a one square metre target. A successful trial was one in which each foot contacted the respective force platforms, where all the markers were in view of the cameras and the ball hit either the target or stumps. Six dynamic overhead throwing trials were performed.

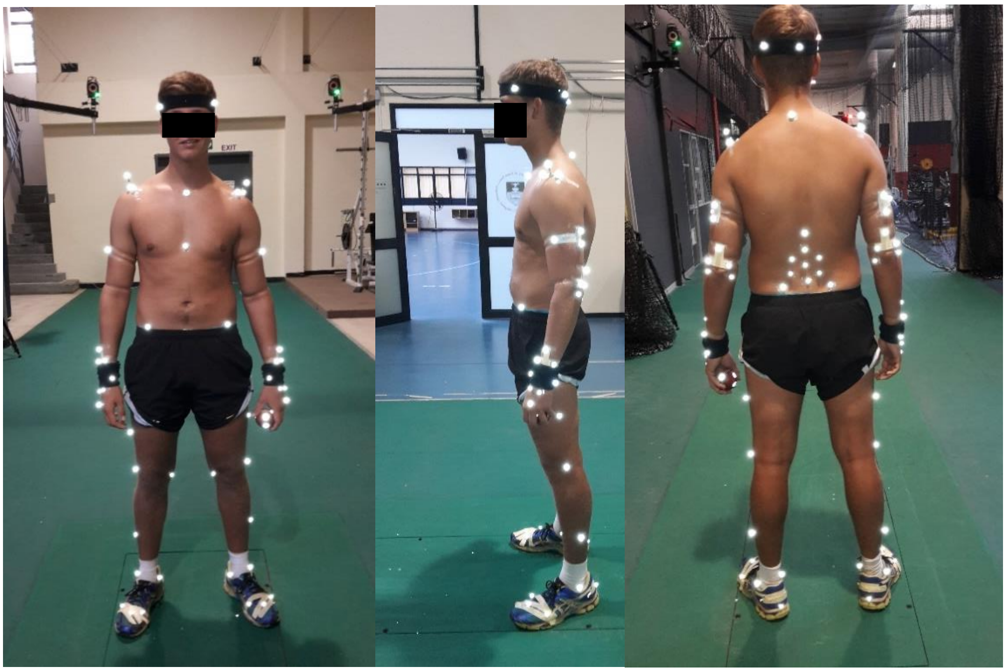

Figure 6.1: The full body marker set as viewed from anterior, lateral and posterior.

6.3.4 Data Analysis

A low-pass fourth-order Butterworth filter with cut-off frequency at 6 and 100 Hz, were used to filter marker trajectory and force plate data respectively. The lower body PlugInGait (Version 3.5)[184] and custom upper-body model were applied to marker trajectories. Newton-Euler inverse dynamics approach was used to calculate 3D joint angles and net resultant joint forces. All joint angles followed the Euler XYZ rotation sequence, except the shoulder which followed an YXY rotation sequence; and were described according to the joint co-ordinate systems recommended by the ISB.[178-180]

Three-dimensional joint forces were expressed in newton (N). Shoulder force was determined as force applied by the trunk to the upper arm; whereas elbow force was calculated as force applied by the upper arm to the forearm.[4] The overhead throw was analysed from neutral shoulder rotation to maximum external rotation (MER) as the preparation/cocking phase; MER to ball release (BR) as the acceleration phase; and BR to the reversal of shoulder rotation (internal to external rotation) indicating dominant arm deceleration (maximum internal rotation).

Data for each participant's dominant throwing limb were averaged over three successful good-quality trials. Joints of interest included the dominant shoulder, elbow and hip (ipsilateral to the dominant throwing arm); thoraco-lumbar and lumbo-pelvic joint angles. Kinematic data are represented as wave-forms that changed continuously throughout the overhead throw and were defined with 101 data points, one for each percentage of the overhead throw. Kinetic data for the shoulder and elbow were determined at critical points in the overhead throwing cycle, including MER, point of BR and maximum shoulder internal rotation (MIR).

6.3.5 Statistical Analysis

Shapiro-Wilk's test was used to screen data for normality of distribution. One-dimensional statistical parametric mapping (1DSPM) one-way ANOVA (SPM[f]) was used to determine differences in the performance of static and dynamic overhead throwing waveform variables. All 1DSPM analyses were implemented using the open source 1DsSPM code (v.M0.4, www.spm1d.org) in Matlab (R2017b, Mathworks Inc., Natick, MA, USA). Where joint kinetic data were normally distributed with equal variance, independent t-tests were performed to determine differences between throwing approaches; whereas, joint kinetic data not normally distributed, were analysed using the Mann-Whitney U test. Significance was set at $p<0.05$.

6.4 RESULTS

Of the 15 cricketers, two were left- and 13 right-handed, with a group mean age of 22.0 ± 3.4 years, mass of 76.9 ± 10.5 kg and height of 1.9 ± 0.8 m. When overhead throwing, the time taken to complete a dynamic throwing cycle was 0.68 ± 0.15 s and a stationary throw cycle was 0.73 ± 0.18 s. No differences in the time taken to complete the total throwing cycle or the time to complete each phase of throwing (MER, BR and MIR), were found between the two throwing approaches (Table 6.1).

Two kinematic waveform differences between stationary and dynamic throwing approaches were found (Figure 6.2). A dynamic approach to overhead throwing demonstrated greater dominant hip flexion between 0-34% and 57-100% ($F= 6.726$; $p=0.01$); and lumbo-pelvic flexion between 57-65% ($F= 6.823$; $p=0.02$) of the throwing cycle, when compared to a stationary approach. No kinematic differences were found in the shoulder, elbow and thoraco-lumbar joints.

Lastly, greater compression ($F=1.036$; $p=0.02$) and posterior forces ($F=1.052$; $p=0.009$) of the shoulder where found at MER, when throwing with a run-up approach, compared to a stationary position (Table 6.2). Conversely, at BR, the shoulder is subjected to significantly less superior force ($F=1.744$; $p=0.005$) while the elbow experiences less compression ($F=4.331$; $p=0.03$), superior ($F=1.212$; $p=0.002$) and medial ($F=1.370$; $p=0.03$) force, when performing a dynamic approach as opposed to a stationary approach.

Table 6.1: Total throwing cycle and joint angles at MER, point of BR and MIR, for this cohort of cricketers, when throwing overhead from a stationary position and running forward to field a ball (dynamic).

	Cricket Cohort (n=15)	
	Stationary	**Dynamic**
Total throwing cycle (s)	0.73 ± 0.18 (100%)	0.68 ± 0.15 (100%)
Preparation	0.32 (45%)	0.35 (51%)
Arm Acceleration	0.07 (9%)	0.03 (4%)
Arm Deceleration	0.17 (23%)	0.16 (24%)
Follow-through	0.17 (23%)	0.14 (21%)
Shoulder (°)		
Maximum External Rotation		
Elevation (+)	91.2 ± 9.3	92.4 ± 7.5
Internal (+)/External (-) rotation	-71.2 (-114.4 – -36.9)	-66.7 (-104.7 – 23.4)
Ball Release		
Elevation (+)	96.1 ± 6.4	93.8 ± 7.3
Internal (+)/External (-) rotation	-63.0 ± 42.4	-51.9 ± 41.5
Maximum Internal Rotation		
Elevation (+)	63.9 ± 16.9	60.8 ± 17.1
Internal (+)/External (-) rotation	-15.0 ± 20.6	-1.4 ± 24.2
Elbow (°)		
Maximum External Rotation		
Flexion (+)/Extension (-)	105.8 (53.3 – 118.1)	83.0 (41.3 – 113.5)
Valgus (+)/Varus (-)	-8.5 ± 6.4	-10.1 ± 4.5
Ball Release		
Flexion (+)/Extension (-)	73.3 ± 26.9	69.0 ± 20.9
Valgus (+)/Varus (-)	-10.8 ± 5.4	-9.1 ± 4.9
Maximum Internal Rotation		
Flexion (+)/Extension (-)	45.7 ± 13.4	47.5 ± 10.3
Valgus (+)/Varus (-)	-1.1 ± 4.7	0.7 ± 4.9

Table 6.2: Shoulder and elbow forces (N) at critical points in throwing cycle for this cohort of cricketers when throwing overhead from a stationary position and running forward to field a ball (dynamic).

	Cricket Cohort (n=15)	
	Stationary	**Dynamic**
Shoulder		
Maximum External Rotation		
Distraction (+)/Compression (-)	-102.2 ± 30.8*	-129.3 ± 31.4*
Superior (+)/Inferior (-)	156.4 ± 77.3	207.9 ± 94.7
Anterior (+)/Posterior(-)	-7.2 ± 14.1*	-21.8 ± 14.5*
Ball Release		
Distraction (+)/Compression (-)	-22.3 ± 26.4	-4.4 ± 20.2
Superior (+)/Inferior (-)	119.8 ± 64.5*	53.1 ± 48.8*
Anterior (+)/Posterior(-)	7.1 (-60.6 – 25.4)	6.6 (-29.2 – 31.3)
Maximum Internal Rotation		
Distraction (+)/Compression (-)	61.4 ± 24.1	68.6 ± 24.5
Superior (+)/Inferior (-)	119.7 ± 35.4	145.9 ± 37.7
Anterior (+)/Posterior(-)	-62.2 ± 35.8	-74.7 ± 30.6
Elbow		
Maximum External Rotation		
Compression (+)/Distraction (-)	88.1 ± 32.1	99.6 ± 32.4
Superior (+)/Inferior (-)	27.8 ± 13.5	31.0 ± 19.2
Medial (+)/Lateral (-)	19.0 ± 29.1	31.4 ± 33.7
Ball Release		
Compression (+)/Distraction (-)	22.2 ± 26.8*	4.0 ± 12.9*
Superior (+)/Inferior (-)	39.5 ± 22.3*	10.9 ± 20.3*
Medial (+)/Lateral (-)	52.7 ± 32.8*	25.8 ± 28.0*

* Significant difference $p < 0.05$

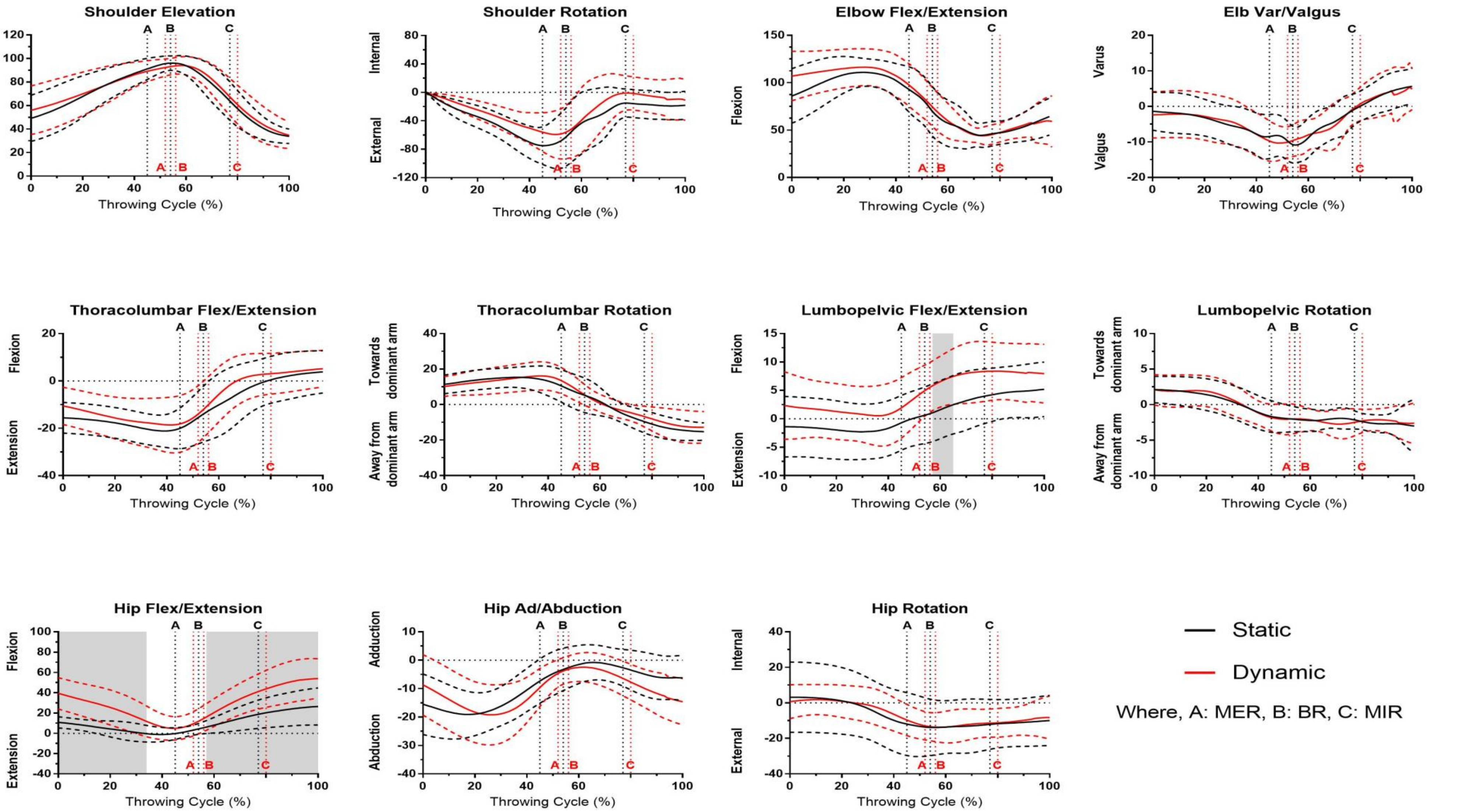

Figure 6.2: Kinematic data over an entire throwing cycle; mean ± 1 standard deviation for overhead throwing in cricketers (n=15) when performed in a static (black) and dynamic (red) position with significant differences between positions ($p < 0.05$, grey shaded band).

6.5 DISCUSSION

The main aim of this study was to determine if differences existed between overhead throws performed from a stationary position and dynamic approach. In order to explore this effectively, it is essential to understand that dynamic GH stability is maintained through the concentric rotator cuff[18-20] and deltoid;[105-107] and eccentric biceps brachii[10] muscular activity from the preparatory phase to point of BR in the overhead throwing cycle, to achieve the range of external rotation needed to generate appropriate ball velocity.[10,11] These muscles generate shoulder compression, superior and anterior forces at MER and contribute to even greater shoulder compression at BR, while an inferior shear of the humeral head develops.[4] Conversely, eccentric action of the teres minor, infraspinatus and posterior deltoid[18] provide a posteriorly directed force on the shoulder, to decelerate the throwing arm.[4]

The results of this study indicate that the shoulder experiences an increase in compressive and posterior forces, at MER; when throwing overhead with a run-up, compared to a stationary approach. While shoulder compression is beneficial for GH stability at MER,[4] the development of a posterior, as opposed to anterior, force highlights potential rotator cuff weakness[18-20] and increased susceptibility for glenoid impingement[16,142] and labral injuries.[4,10] Interestingly, while both throwing approaches demonstrated similar shoulder elevation kinematics, the dynamic approach demonstrated a rapid change in lumbo-pelvic flexion from the preparatory phase to the point of BR. It is known that the latissimus dorsi is eccentrically loaded nearing MER,[185] but also synergistically controls lumbar lordosis.[186] Consequently, an increase in lumbo-pelvic flexion may eccentrically load the latissimus dorsi to a greater extent, resulting in increased shoulder joint compression. In addition, an associated increase in posterior shoulder force is expected to occur, as the latissimus dorsi demonstrates the least flexibility in this position.[63,187] While this finding is observed in the dynamic throw, it fails to explain the posterior shoulder force obtained during stationary throwing. A plausible explanation for this could be that these cricketers have an underlying musculoskeletal imbalance in which the pectoralis major and subscapularis muscles are too weak and the latissimus dorsi too short,[63,187] to generate the anterior shoulder force previously seen in baseball pitchers at MER.[4]

Remarkably, the development of a greater inferior shear at BR, relative to MER, was found when cricketers throw dynamically compared to a stationary approach. Although the inferior shear noted is similar in magnitude to that reported for baseball pitchers, a lack of the concomitant increase in shoulder compression occurred.[4] As previously discussed, the significantly greater lumbo-pelvic flexion noted at BR, mechanically overloads the latissimus dorsi.[63,187] Subsequently, the concentric contraction of the latissimus dorsi required to extend, adduct and horizontally adduct the throwing shoulder to generate the internal rotation torque necessary to throw,[187] may be compromised.

A resultant deficit in both shoulder compression[63,187] and the GH horizontal adduction, necessary to decelerate the throwing arm[18,19] could be expected to occur. These findings indicate that cricketers may be reliant on the rotator cuff (specifically the subscapularis) and pectoralis major[63,187] to synergistically assist the latissimus dorsi at BR, when throwing dynamically. As dynamic GH stability is provided by the rotator cuff during BR,[18-20] a loss of shoulder compression during arm deceleration highlights potential weakness of the rotator cuff musculature and increased risk of injury, in this cohort of overhead throwing sportsmen.

Generally, the lower forces noted at both the shoulder and elbow at the point of ball release during a dynamic approach to throwing, could be attributed to the cumulative effect of lower limb kinematics which has been shown to generate 51-55% of the energy required to throw in baseball pitchers.[8] A breakdown in the kinetic chain, as a result of dysfunctional or absent lower limb kinematics, has been shown to increase the load on the shoulder and elbow by 23-27% when serving in tennis.[188] A similar trend is displayed at BR in this study. Specifically, cricketers experience 20-44% and 18-49% more shoulder and elbow loading respectively, when throwing from a stationary approach. Consequently, the potential energy contribution of the lower limbs to overhead throwing in cricketers, is highlighted.

Unsurprisingly, no differences in upper limb kinematics were found for cricketers when throwing overhead, irrespective of a stationary or run-up approach. Concurrent findings have been reported for elite handball players,[183] however, in this handball study maximal pelvic, trunk and shoulder internal rotation, as well as elbow extension torques were found to be similar between standing throws with and without run-ups, resulting in a moderate relationship between ball velocity and run-up.[183] The potential relationship between ball velocity and run-up in the cricketers in our study, is highlighted by the greater angles of hip and lumbo-pelvic flexion, which may increase the lower limb contribution to the energy generated, at various phases of the dynamic throwing cycle.

The greater dominant hip flexion angle during the preparatory phase is thought to occur for two reasons. Firstly, cricketers were required to mimic a fielding scenario by running forward and bending or squatting down to collect the ball off the floor and then throwing the ball. Conversely, when throwing with a stationary approach, the dominant hip remained in relatively neutral flexion/extension, as the throw was performed in a standing position with a step forward by the non-dominant leg. Secondly, it is surmised that the increased hip flexion angle is maintained when throwing with a dynamic approach and utilised by cricketers to lower their centre of gravity and point of BR in order to obtain a flatter ball trajectory.[18,39]. This position is known to increase ball velocity in baseball pitchers[17-19] and reduce flight time when cricketers throw from a variety of approaches.[39]

Further, it is well documented that ball velocity is directly influenced by the degree of forward trunk lean in baseball pitchers.[17,62,185] The description of forward trunk lean angular measurement used in baseball players[185], is similar to the ISB joint co-ordinate description for lumbo-pelvic flexion,[59,178-180] used in this study. Therefore, it is suggested that when throwing with a dynamic approach, cricketers are more reliant on lumbo-pelvic flexion to generate ball velocity, than when they throw with a stationary approach. Furthermore, the increased dominant hip flexion angle occurring specifically around BR (57-65% of the total dynamic throwing cycle), is thought to enhance the degree of lumbo-pelvic flexion, as electromyographic studies have correlated iliopsoas and rectus femoris muscle activity during hip flexion, with increased lumbar lordosis[189] and anterior pelvic tilt,[190] respectively. Consequently, this mechanism of increased hip flexion in the latter third of the dynamic throwing cycle (>65%) is thought to aid in whole body, trunk and throwing arm deceleration, similar to that described for baseball pitchers.[17,18,185] It can therefore be deduced that the different lower limb and trunk kinematics utilised for overhead throws, with and without a run-up, may influence ball velocity.

Further research is required to determine the relationship between lower limb kinematics and the performance of overhead throwing in a variety of approaches. In addition, the segmental contribution of a cricketer's kinetic chain to ball velocity, requires investigation. As this study only considered the kinematics of the dominant hip, it is recommended that future studies assess bilateral lower limb kinematics in order to determine the potential relationship between dominant and non-dominant lower limbs to overall throwing performance.

6.6 CONCLUSION

Cricketers are able to adapt to lower body and trunk movement in various throwing approaches, thereby enabling similar throwing arm movement. When throwing with a dynamic approach, cricketers experience greater hip flexion in the preparatory phase. In addition, increased hip and lumbo-pelvic flexion occurs at BR. These biomechanical variances contribute to cricketers experiencing approximately double the quantity of shoulder compression and posterior force at MER, indicating a potentially higher risk for injury. Conversely, half of the shoulder compression is measured during BR. Consequently, the potential risk for shoulder injury in cricketers may be associated with the throwing approach utilised during fielding. The differences in shoulder load at MER and BR may provide insight into the specific shoulder conditioning exercises and range of movements required. Further, knowledge of these forces may be beneficial to coaches, trainers and cricketers when performing different throwing approaches during practices and/or matches.

Summary Box

- Cricketers adapt to lower limb and trunk movement allowing the throwing arm to maintain a similar pattern of movement, irrespective of a static or dynamic approach to throwing.
- Increased angles of lumbo-pelvic and dominant hip flexion are thought to increase forward trunk lean and potentially ball velocity when dynamically approaching a throw.
- Substantially higher shoulder compression and posterior force at MER occurred with a dynamic approach to throwing, potentially increasing the risk of injury at this point in the overhead throwing cycle.
- The contribution effect of lower limb kinematics to overhead throwing performance is highlighted by the 18-49% reduction in shoulder and elbow forces at BR, during a dynamic approach to overhead throwing.
- Coaches, trainers and cricketers should be cognisant of the differences in shoulder load associated with throwing approach when fielding during practices and/or matches

PART 3

CHAPTER 7 – THE CRICKETER’S SHOULDER: GIRD AND OVERHEAD THROWING BIOMECHANICS

7.1 ABSTRACT

Objectives: To determine the association between glenohumeral internal rotation deficit (GIRD) and the kinematics and kinetics of overhead throwing in cricketers from a stationary position and run-up approach.

Design: Cross-sectional cohort study

Setting: Institutional biomechanical laboratory

Methods: Fifteen cricketers completed a shoulder screening battery, including a shoulder function questionnaire and 14 musculoskeletal tests. Kinetic and kinematic data were obtained during an overhead throw from a stationary and run-up approach. A linear regression was used to determine potential relationships between GIRD, and musculoskeletal screening variables and discrete shoulder kinetics for both throwing approaches. One-dimensional statistical parametric mapping regression was conducted to assess relationships between GIRD and throwing kinematics.

Results: When throwing overhead from a stationary position, GIRD was associated with reduced hip abduction ROM during 0-23% of the throwing action (p=0.002); reduced superior shoulder (p=0.003) and elbow compressive (p=0.009) forces at MER. Further, GIRD was associated with increased posterior shoulder force at MIR for both stationary (p=0.013) and run-up approaches (p=0.03) to overhead throwing. Lastly, GIRD was associated with reduced dominant hip passive external rotation ROM (p=0.03).

Conclusion: Cricketers with GIRD throw across the body by increasing dominant hip internal rotation ROM (associated with reduced passive hip external rotation) in an attempt to obtain greater GH horizontal adduction for adequate arm deceleration. Increased GIRD was associated with greater posterior shoulder forces which may potentially increase the risk for injury in these cricketers.

7.2 INTRODUCTION

The shift in glenohumeral (GH) rotation arc is a well-documented adaptation found in overhead athletes.[40]. It is characterised by a gain in external rotation (ERG) and concomitant reduction in internal rotation (GIRD) of the shoulder, while maintaining a rotational range of 180°.[41] In baseball, the development of this rotational shift is not only attributed to humeral retroversion[9] but also the overload subjected to the posterior shoulder capsule (PSC) during the late cocking and deceleration phase of throwing.[12] During cocking the PSC and posterior rotator cuff are strained with an ERG to withstand an internal rotation torque of up to 80 Nm.[4,191] Conversely, during deceleration, these structures are eccentrically loaded to resist horizontal adduction by providing a posteriorly directed force of up to 400 N.[4,191]. Consequently, repetitive throwing in baseball pitchers causes the PSC to become thickened; and contributes to an increased scapula upward rotation at 60°, 90° and 120° GH abduction, resulting in the maintenance of the subacromial space (measured as acromiohumeral distance (AHD)).[100]

Humeral retroversion has yet to be measured in cricketers, but these overhead throwing athletes do exhibit PSC stiffness and a preserved AHD.[192] Interestingly, downward scapula rotation from rest to 90° has been noted in cricketers,[192] indicating that AHD preservation potentially occurs as a result of increased strength in the GHER and a high GHER:GHIR ratio[116]. While this anomaly has been reported in volleyball players,[116] cricketers demonstrate reduced GHER strength with a normal GH ER:IR ratio, in addition to a loss of total GH rotational ROM (TROM) and GIRD.[192] This may be partly attributed to the muscular imbalances noted around the shoulder,[7,8,32,192] as a similar association between TROM, GIRD, and shoulder strength has been reported for baseball pitchers.[94] Notably, in the presence of shoulder pain, pitchers have been found to experience a significant reduction in TROM;[93,145] greater GIRD;[93,145] weakness of the middle trapezius and supraspinatus muscles; and stronger GHIR muscle strength.[93,94] Similar findings have been reported for cricketers with non-traumatic shoulder injuries.[192] Consequently, injury surveillance studies have identified cricketers as a high risk population for the development of shoulder pain and/or injury.[7,27-32,193]

The GH rotational laxity observed in baseball pitchers is advantageous for overhead throwing as the humeral acceleration achieved, provides the greatest segmental contribution (6000-8000°/s) to ball velocity.[10,18] This may further be enhanced by ERG;[10,11] increased strength of the GH external rotators[11] and non-dominant hip rotational flexibility,[194] in the cocking phase specifically.[10,18] However, this phase in overhead throwing is where previous research has identified biomechanical differences between baseball pitching and cricket overhead throwing.[37,109] In the preparation/cocking phase, cricketers have demonstrated lower ranges of elbow flexion[37,109] and GH external rotation (Chapter 5), than baseball pitchers.

Consequently, cricketers may not achieve the ERG necessary to enhance humeral rotational torque and ultimately ball velocity. The lack of ERG demonstrated by cricketers when throwing overhead from a stationary position or with a run-up (Chapter 6) is surprising when considering the musculoskeletal adaptations, like GIRD are inherent to the cricketer's shoulder.[192] Glenohumeral internal rotation deficit was found to increase the risk for shoulder injury when pitching overhead,[17-20] although this risk may be attenuated by a GH TROM loss of >5°.[185,195,196] Cricketers tend to display both GIRD and a GH TROM loss, indicating that GIRD is likely to be pathologic.[191] Consequently, the influence of GIRD on the overhead throwing biomechanics of cricketers is of interest to better understand the potential contribution of this musculoskeletal variable to shoulder injury. The aim of this study was to determine the association between GIRD and the kinematics and kinetics of overhead throwing performed by cricketers from a stationary position or following a run-up.

7.3 METHODS

7.3.1 Participants

Fifteen healthy male cricketers currently representing a national, elite or amateur franchise team; were invited to participate in this study. These participants had no cervical or neurological symptoms, history of shoulder surgery and/or traumatic shoulder injury or current shoulder pain. Ethical approval for this study was obtained from the Human Research Ethics Committee of the study institution (Appendix VI). All eligible participants provided written informed consent prior to the commencement of the study (Appendix IV and VII).

7.3.2 Measurement Procedures

Participants attended a single testing session where they completed a questionnaire to obtain demographic information; training, competition and injury history, prior to the commencement of the kinematic and kinetic capture of overhead throwing. In addition, anthropometric measurements were recorded and the shoulder screening protocol (Appendix V) previously utilised to determine the musculoskeletal risk factors associated with shoulder injuries in cricketers was implemented (Chapter 4), with the exception of ultrasonographic measurements.[192]

7.3.3 Overhead Throwing Data

The detailed methodology is described in Chapter 6. Briefly, participants completed a standard fielding warm-up and four overhead throws prior to the throwing trial. Each throwing trial comprised of six overhead throws each from a stationary position and when running forward to collect the ball from the ground. Throws were directed towards a set of stumps, surrounded by a one metre target, positioned 20 m away.

During these trials, synchronised collection of marker trajectories and force platform data were sampled in Vicon Nexus (Vicon, Oxford Metrics Ltd., Oxford, UK). A trial was considered successful if each foot contacted the respective force platforms, all markers were in view of the cameras and the ball hit either the stumps or target. The three-dimensional shoulder, elbow, thoraco-lumbar, lumbo-pelvic and dominant hip joint angles, as well as the shoulder and elbow forces are represented as wave-forms that changed continuously throughout the overhead throw and were defined with 101 data points, one for each percentage of the overhead throwing task from neutral shoulder rotation to the reversal of shoulder rotation at follow through. Shoulder and elbow forces were extracted at the critical points of MER, point of BR and MIR.

7.3.4 Statistical Analysis

Data were screened for normality of distribution using Shapiro-Wilk's test. Musculoskeletal screening data were analysed using SPSS version 24 (IBM, Armonk, New York, USA). A linear regression was performed to determine the relationship between each musculoskeletal variable and GIRD. GIRD was defined as: *"The difference between dominant shoulder internal rotation deficit and external rotation gain."*[41] Only the musculoskeletal parameters pertaining to the dominant shoulder were included in the data analysis. In addition, bilateral hip rotational flexibility and gluteus medius strength were analysed, as these musculoskeletal variables are known to influence throwing performance in baseball pitchers.[10,11,18,94,194] Overhead throwing data were analysed using one dimensional statistical parametric mapping (1DSPM). The relationship between kinematic waveform data and GIRD, was tested using a linear regression (SPM[f]). All 1DSPM analysis were implemented using the open source 1DsSPM code (v.M0.1, www.spm1d.org) in Matlab (R2017b, Mathworks Inc., Natick, MA, USA). Data are presented as mean ± standard deviation unless otherwise stated. Significance was set at $p<0.05$.

7.4 RESULTS

Fifteen cricketers qualified to participate in this study and presented with a mean age of 22.0 ± 3.4 years, height of 1.9 ± 0.8 m and mass of 76.9 ± 10.5 kg (Table 7.1). Nine fast bowlers, two spinners and four batsmen (two of which were wicket keepers), were included in this cricketing cohort. Three cricketers had a history of shoulder injury which occurred in one (n=2) and four (n=1) seasons prior to testing.

All musculoskeletal screening variables are presented in Table 7.1. Interestingly, a low mean shoulder function score (KJOC score <90%)[132] is reported for this cohort despite the absence of shoulder injury, indicating a reduced shoulder function in this group. In addition, the dominant shoulder of this cohort presented with a GH TROM loss >41°; GIRD of 41.7° and ERG of 6.4°.

When the musculoskeletal profile of the dominant shoulder in this cohort of pain-free cricketers (n=15) is compared to the known reference data for overhead athletes, a GH TROM loss of 27.2°;[40] GIRD of 5.4°[40] and GH external rotation insufficiency of 12.5°[40] greater than the norm for overhead athletes, is noted. In addition, a consistently downwardly rotated scapula from rest to 90° GH elevation;[40] poor UT, SA, GHER and GHIR strength, yet greater LT strength;[113,153] relatively normal PML[113] but substantial PSC stiffness,[155] is demonstrated in these cricketers when compared to known reference data for overhead athletes. Further, a loss in bilateral hip total, external and internal rotational ROM;[99] and considerably lower gluteus medius strength,[99] was noted.

The only musculoskeletal relationship determined for GIRD (Table 7.2) was the negative correlation with dominant hip passive external rotation ROM ($F(1;13)=5.850$;$p<0.03$; $r=-0.557$), indicates that increased GIRD was associated with a reduction in the range of dominant hip passive external rotation.

A single waveform relationship was found for GIRD (Figure 7.1). Increased GIRD was negatively correlated with hip abduction between 0-23% of the overhead throwing cycle from a stationary position ($F=3.042$; $p=0.002$). Consequently, cricketers with increased GIRD utilised less hip abduction in the preparatory phase of overhead throwing from a stationary position.

In addition, various discrete kinetic relationships were noted for GIRD at MER and MIR (Table 7.2 and 7.3). GIRD correlated negatively with superior shoulder force ($F(1,25)=10.350$; $p=0.003$; $r=-0.541$) and elbow compression ($F(1,25)=7.808$; $p=0.009$; $r=-0.488$) at MER. Conversely, GIRD was positively correlated with posterior shoulder force at MIR ($F(1,25)=7.194$; $p=0.013$; $r=0.472$). A similar positive correlation between GIRD and posterior shoulder force at MIR ($F(1,12)=5.840$; $p=0.03$; $r=0.572$) was found when throwing overhead following a run-up. These findings indicated that cricketers with increased GIRD experienced a decrease in the quantity of superior shoulder force and elbow compression at the end of the cocking phase, when throwing from a stationary position. Conversely, greater GIRD was associated with greater posterior shoulder force during arm deceleration, when throwing from a stationary position and following a run-up approach).

Table 7.1: The descriptive (A) and musculoskeletal characteristics of the upper limb (B) and lower limb (C) of the cricketers.

A. Descriptive Variables	**Cricketers (n=15)**
Age (years)	*22.0 ± 3.4*
Height (m)	*1.9 ± 0.8*
Mass (kg)	*76.9 ± 10.5*
Dominance	
Left	2
Right	13
Speciality	
Fast Bowler	9
Spin Bowler	2
Batsmen	4
History of Previous Injury	
Yes	3
No	12
KJOC Score (%)	*80.8 ± 12.0*

B. Musculoskeletal Profile of Upper Limb	**Shoulder**	**Cricketers**	**Reference Data**
GH Rotational ROM (°)			
Total	Dominant	*138.3 ± 14.7*	*165.5 ± 14.4*[40]
Internal	Dominant	*41.9 ± 9.0*	*56.5 ± 12.5*[40]
External	Dominant	*96.4 ± 13.8*	*108.9 ± 9.0*[40]
Upward Scapula Rotation (°)			
At rest	Dominant	*-8.0 ± 8.7*	*6.4 ± 4.7*[40]
At 45° GH abduction	Dominant	*-3.5 ± 7.3*	*Unknown*
At 90° GH abduction	Dominant	*9.9 ± 5.4*	*14.2 ± 6.5*[40]
At 120° GH abduction	Dominant	*22.5 ± 5.6*	*22.4 ± 6.3*[40]
Isometric Muscle Strength (N)			
Upper Trapezius	Dominant	*148.4 ± 15.5*	*158.6 ± 47.7*[113]
Serratus Anterior	Dominant	*136.2 ± 22.3*	*154.8 ± 61.9*[113]
Lower Trapezius	Dominant	*72.8 ± 17.9*	*67.2 ± 18.6*[153]
GH External Rotators (GHER)	Dominant	*104.9 ± 30.9*	*147.6 ± 36.0*[153]
GH Internal Rotators (GHIR)	Dominant	*144.8 ± 41.9*	*178.5 ± 38.8*[153]
GHER:GHIR	Dominant	*0.73 ± 0.12*	*0.71 – 1.08*[154]
PM Length (cm)	Dominant	*12.9 ± 0.7*	*11.7 ± 1.2*[113]
PSC Flexibility (°)	Dominant	*13.9 ± 5.3*	*45.9 ± 5.9*[155]

C. Musculoskeletal Profile of the Lower Limb	**Hip**	**Cricketers**	**Reference Data**
Hip Rotational ROM (°)			
Total	Dominant	*58.2 ± 5.7*	*75.6 ± 5.9*[156]
	Non-dominant	*57.7 ± 7.8*	*75.3 ± 7.8*[156]
Internal	Dominant	*24.6 ± 6.4*	*34.6 ± 4.4*[156]
	Non-dominant	*22.7 ± 5.8*	*34.4 ± 6.1*[156]
External	Dominant	*33.6 ± 4.2**	*41.0 ± 6.3*[156]
	Non-dominant	*34.9 ± 7.0*	*40.9 ± 8.1*[156]
Isometric Muscle Strength (N): Gluteus Medius	Dominant	*189.4 ± 35.2*	*406.0 ± 61.8*[156]
	Non-dominant	*188.4 ± 33.6*	*410.9 ± 70.6*[156]

Data are expressed as mean ± standard deviation.

*Musculoskeletal variables correlated with GIRD

Table 7.2: Correlations between GIRD and the respective musculoskeletal variables, shoulder and elbow forces for this cohort of cricketers.

	r-value	p-value
Range of Motion (°)		
Dominant		
Shoulder Internal Rotation	-0.590	0.02
Hip External Rotation	-0.557	0.03
Non-dominant		
Shoulder Internal Rotation	0.885	<0.0001
Total shoulder rotational	0.653	0.008
Kinetics of Overhead Throwing with a Stationary Approach (N)		
Maximum External Rotation		
Shoulder Superior Force	-0.541	0.003
Elbow Compression	-0.488	0.009
Maximum Internal Rotation		
Shoulder Posterior force	0.472	0.013
Kinetics of Overhead Throwing with a Run-up (N)		
Maximum Internal Rotation		
Shoulder Posterior force	0.572	0.03

Table 7.3: A comparison of shoulder and elbow forces at critical points during overhead throwing in cricketers from a stationary position and with a run-up (dynamic).

	Throwing Cohort (n=15)	
	Stationary	**Dynamic**
Shoulder		
Maximum External Rotation		
Distraction (+)/Compression (-)	-102.2 ± 30.8	-129.3 ± 31.4
Superior (+)/Inferior (-)	156.4 ± 77.3*	207.9 ± 94.7
Anterior (+)/Posterior(-)	-7.2 ± 14.1	-21.8 ± 14.5
Ball Release		
Distraction (+)/Compression (-)	-22.3 ± 26.4	-4.4 ± 20.2 20
Superior (+)/Inferior (-)	119.8 ± 64.5	53.1 ± 48.8
Anterior (+)/Posterior(-)	7.1 (-60.6 – 25.4)	6.6 (-29.2 – 31.3)
Maximum Internal Rotation		
Distraction (+)/Compression (-)	61.4 ± 24.1	68.6 ± 24.5
Superior (+)/Inferior (-)	119.7 ± 35.4	145.9 ± 37.7
Anterior (+)/Posterior(-)	-62.2 ± 35.8*	-74.7 ± 30.6*
Elbow		
Maximum External Rotation		
Compression (+)/Distraction (-)	88.1 ± 32.1*	99.6 ± 32.4
Superior (+)/Inferior (-)	27.8 ± 13.5	31.0 ± 19.2
Medial (+)/Lateral (-)	19.0 ± 29.1	31.4 ± 33.7
Ball Release		
Compression (+)/Distraction (-)	22.2 ± 26.8	4.0 ± 12.9
Superior (+)/Inferior (-)	39.5 ± 22.3	10.9 ± 20.3
Medial (+)/Lateral (-)	52.7 ± 32.8	25.8 ± 28.0

*Kinetic variables correlated with GIRD

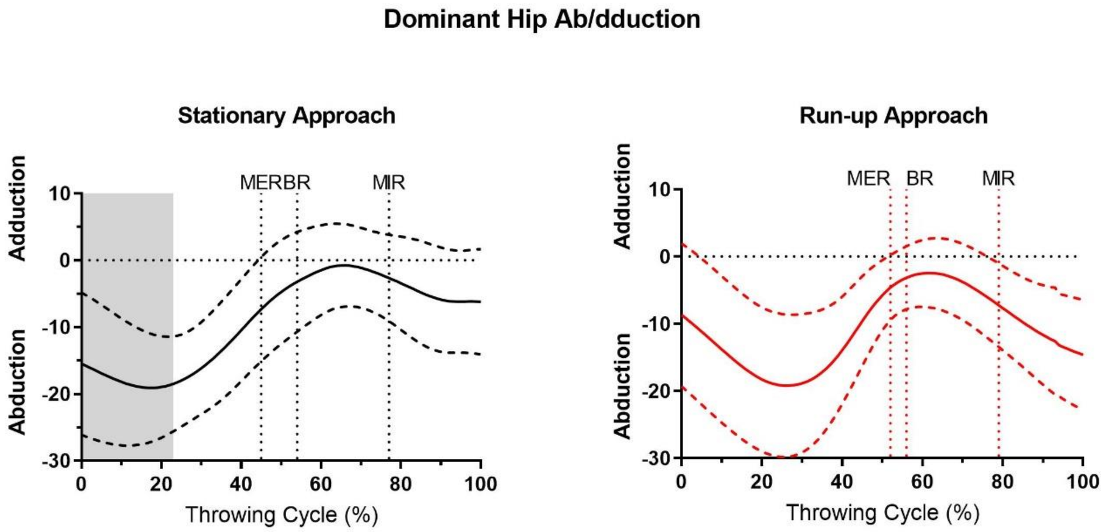

Figure 7.1: Dominant hip ab/dduction kinematic data over an entire throwing cycle; mean ± 1 standard deviation for overhead throwing with a stationary (black) and run-up (red) approach in cricketers (n=15). Significant negative relationship with GIRD ($p<0.05$), grey shaded band.

7.5 DISCUSSION

An association between GIRD and lower ranges of dominant hip abduction ROM was observed during the preparatory phase of overhead throwing from a stationary position. Whether these cricketers experience a delay, or an actual reduction in the range of, hip abduction utilised in the preparatory phase of overhead throwing cycle, has yet to be determined. Nonetheless, both instances may result in a shorter stride which decreases the distance available to generate the linear and angular velocity required by the lumbo-pelvic and thoraco-lumbar joints for optimal energy production and transfer to the dominant throwing arm.[17,18] Consequently, these cricketers are thought to throw off a smaller base of support which may contribute to early forward rotation of the pelvis and trunk and creates a lag in the distal kinetic chain whereby the dominant throwing arm is positioned behind the body.[17-20] Ultimately, the posterior shoulder is overloaded as it attempts to either compensate for, or maintain, throwing performance and hence GIRD develops.[17-20] Weakness in dominant hip abduction has previously been associated with posterior superior labral tears of the shoulder in overhead athletes, specifically baseball pitchers.[22] Although no significant relationship between GIRD and dominant hip GM strength was noted in this study, this cohort demonstrates substantially lower hip abduction strength when compared to the reference data for baseball. Further investigation is required to determine whether cricketers develop GIRD as a consequence of kinetic chain breakdown (weak hip abductor strength); or utilise less hip abduction ROM to overcome GIRD when throwing overhead from a stationary position.

Unsurprisingly, this study found an association between GIRD and reduced superior shoulder force and elbow compression, at MER when throwing overhead from a stationary position. Superior and anterior humeral head translation occurs when the PSC stiffens and shortens,[90] a structural anomaly observed in this group of cricketers. Subsequently, less superior shoulder force is required by the co-contraction of the rotator cuff (specifically the supraspinatus muscle) and deltoid to stabilise the shoulder when positioned in MER. As anterior humeral translation is reduced by the long head of biceps contraction,[104] an elbow flexion torque is generated in this position and consequently, less elbow compression occurs.[182] Interestingly, no direct association between GIRD and the isometric strength of the GHIR and GHER was found in this study. This may be that isometric strength testing was performed in a 90/90 position, with the elbow supported.[16] During graduated isometric external rotation exercises, the external rotation capacity of the supraspinatus muscle, in conjunction with the infraspinatus muscle, increases in unsupported positions.[107] In addition, the maximal voluntary contraction (MVC) of the subscapularis muscle has been reported as 9% during dynamic external rotation tasks with changing levels of arm support.[106] Consequently, the isometric strength measurements of GHER and GHIR would be lower in a supported compared to unsupported position. Based on the lack of association between GIRD, GHER and GHIR reported in this study; it is recommended that isometric strength testing of the GHER and GHIR be performed with the arm unsupported and potentially at different points in ROM. Nevertheless, the reduction in forces experienced by the shoulder and elbow at MER, highlights the effect of PSC stiffness in this cohort of cricketers and is suggestive of global rotator cuff weakness. Further, it is well known that when GIRD exceeds 20° during this phase of throwing, the risk for GH labral tears, rotator cuff impingement and/or strains, increases incrementally.[8,17-20] Therefore, this cohort is at high risk for injury, as GIRD was measured as 41.7°.

The positive relationship between GIRD and posterior shoulder force at MIR, irrespective of throwing approach, may be explained by understanding the importance of this force to decelerate the throwing arm.[4] In baseball pitching, arm deceleration is facilitated by approximately 35° GH horizontal adduction.[18] The kinematic waveform data for GH horizontal adduction was not analysed in this study, however GH horizontal adduction ROM has been used as a static clinical measure of PSC flexibility[99] and replicated in this study. The dominant shoulder of the cricketers presented with only 13.9° of GH horizontal adduction which is three times lower than the 45.9° measured in baseball pitchers.[155] Therefore the ability of cricketers to generate the posterior shoulder force required to facilitate arm deceleration, in the absence of sufficient GH horizontal adduction, is questioned.

It is important to note that a linear relationship was found between GH horizontal adduction and internal rotation ROM,[99] indicating that PSC flexibility directly influences GIRD.[4,12,191] Interestingly, this study found that an increase in GIRD is associated with a reduction in dominant passive hip external rotation ROM. It is therefore thought that cricketers with GIRD may actively engage the dominant hip internal rotators to decrease passive external rotation ROM when throwing overhead. A resultant premature forward rotation of the pelvis occurs.[17,18,20,21] Together with the utilisation of lumbo-pelvic flexion, as opposed to thoraco-lumbar flexion (Chapter 6), cricketers may throw across body[17,18,20,21] to aid arm deceleration. Consequently, greater posterior force is required to decelerate not only the throwing arm, but the whole body, in a cricketer with GIRD. An associated increase in the potential risk for injury to the posterior rotator cuff and superior labrum,[10] is therefore highlighted in this cohort. However, it has yet to be determined whether the throwing technique described above occurs as a result or contributes to the development of GIRD and other musculoskeletal idiosyncrasies in cricketers. In addition, this technique may alter the trajectory of the ball, potentially influencing the throwing biomechanics and the performance parameters of ball velocity and accuracy. Finally, individual variability in both musculoskeletal profile and throwing biomechanics may occur in response to differing throwing loads, as well as the technical nature of this overhead movement pattern.

The increased susceptibility of cricketers to shoulder and elbow injury when throwing overhead with GIRD >20°, has been highlighted in this study. This may be further amplified by the TROM loss of 6.9°. Currently, the predictive nature and cut-off values for TROM, GIRD and PSC flexibility for shoulder injury in cricketers has yet to be determined.[192] However, various studies conducted in baseball pitching, have associated a TROM difference >5° with a 2.5 and 2.6 times greater risk for shoulder[185,195,196] and elbow[197] injury, respectively; and in conjunction with GIRD >20°[13] have shown internal shoulder impingement to occur.[191] It is therefore plausible that cricketers, as a general population, may be at increased risk for shoulder and elbow injury, when throwing overhead.

It is vitally important that cricketers be taught to throw well, which may lessen the propensity to develop the ROM, strength and force adaptations associated with injury. Further, clinicians tasked with the treatment and rehabilitation of cricketers should be cognisant of the influence of GIRD on overhead throwing performance. Cricket strengthening programs should specifically target GHER, GHIR and hip abduction strengthening; as well as flexibility of the PSC and hip rotators. Specific plyometric shoulder rotational exercises, such as the reverse throw using a plyo-ball or rebounder, are recommended to ensure sufficient conditioning for the forces which inherently occur during throwing.

This study only assessed the association between GIRD and overhead throwing biomechanics. Future studies should consider the impact of other musculoskeletal variables, such as GH rotational strength (measured with elbow unsupported) and scapula dyskinesis, on overhead throwing biomechanics in cricketers. In addition, the influence of all musculoskeletal variables on the performance parameters of ball velocity and accuracy when throwing, should be considered. Finally, studies which wish to elaborate on the three-dimensional kinematics of overhead throwing in cricketers, should consider including a measurement of GH horizontal adduction ROM.

7.6 CONCLUSION

This study demonstrates the association between GIRD and overhead throwing biomechanical parameters. The increased posterior force demonstrated at MIR when cricketers throw overhead (irrespective of approach) highlights the susceptibility of the shoulder to injury. Additionally, GIRD >20° together with the lower superior shoulder force and elbow compression found at MER when throwing from a stationary position, are indicative of rotator cuff weakness which may increase the risk for shoulder injury.

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Conflicts of interest

No conflicts of interest.

Summary box

- Cricketers engage the dominant hip internal rotators, creating early pelvic rotation and utilising lumbo-pelvic flexion, resulting in a cross body throw which increases GIRD
- GIRD is associated with greater posterior shoulder force at MIR, irrespective of throwing approach, potentially increasing the risk for posterior rotator cuff and labral injuries
- GIRD is associated with less superior shoulder force and elbow compression at MER, when throwing from a stationary approach, indicating potential rotator cuff weakness which may impact ball velocity
- Rehabilitation of GIRD in cricketers should include hip and shoulder strengthening and flexibility

SUMMARY

CHAPTER 8 – SUMMARY AND CLINICAL PERSPECTIVES

8.1 SUMMARY

Bowling and batting are the two cricket disciplines which have received the most attention in the domain of research. This may reflect the lesser importance placed on the fielding discipline, until more recently. As such, very little is known about the cricketer's shoulder with regards to injury and throwing biomechanics.

The aim of this thesis was to understand the impact of cricket on the shoulder joint in elite South African cricketers. The findings of this thesis highlight numerous factors which fulfil the first two steps of van Mechelen's approach to sports injury research[26] (Figure 8.1).

Part 1: Risk factors for shoulder injury

The incidence and impact of shoulder injuries in elite South African cricketers was determined over a season, irrespective of time-lost to match and training participation (Chapter 3). Subsequently, the number of shoulder injuries recorded were approximately three and a half times more than that previously reported in a similar cohort of South African cricketers.[27] Importantly, almost three quarters of these shoulder injuries were non-time-loss, resulting in an alteration in throwing technique or fielding position of injured cricketers when participating in practices and matches potentially limiting the players fielding performance. Further, the prevalence of shoulder injuries was highlighted by the number of cricketers presenting with a history of previous shoulder injury. In addition, the majority of cricketers recorded decreased shoulder functional ability, irrespective of previous and/or current injury. These findings emphasised the necessity to investigate the musculoskeletal profile of a cricketer's shoulder (Chapter 4), throwing kinematics (Chapters 5 and 6), as well as the potential effect of these respective variables on shoulder injury risk (Chapter 4-7).

Remarkably, pre-season shoulder screening found the musculoskeletal profile of an elite South African cricketer's shoulder to be atypical of the classic *"thrower's paradox"* inherent to baseball pitching shoulders.[40] Specifically, cricketers presented with a loss in TROM, GIRD and no ERG; scapula dyskinesis and preserved AHD measurements, although the SsT was thicker than the normal. These findings highlighted the potential vulnerability of this population of overhead throwing sportsmen to shoulder injury. In addition, it introduces the possibility that young developing cricketers may not get sufficient exposure to the throwing workload required to obtain the humeral adaptations which appear to be advantageous at a later stage.

Three of the seventeen pre-season shoulder screening variables were associated with seasonal shoulder injury, including: post-season KJOC scores (questionnaire measuring shoulder functional ability), dominant shoulder SsT and non-dominant shoulder PML. However only dominant shoulder SsT ≥5.85mm and non-dominant PML ≤12.85cm significantly predicted in-season shoulder injury (Chapter 4).

The different shoulder musculoskeletal profile demonstrated by cricketers raised the question as to how these sportsmen throw overhead, providing the overriding question for Part 2 of the thesis. In addition, this information was part of an infographic complied for the purposes of educating the medical and conditioning professionals within the Cricket South Africa pipeline (Figure 8.2).

Part 2: Biomechanics of overhead throwing

The description of 3D overhead throwing biomechanics in cricketers was conducted to better understand our cricketing cohort's throwing technique. Other than the preparatory arc observed, it was interesting to find that cricketers demonstrate similar overhead throwing kinematics from a stationary position to that extensively described in baseball pitching[18,19] (Chapter 5). However, the potential risk for shoulder injury in cricketers when throwing overhead was highlighted by the substantially lower MER achieved. Biomechanically, this variance is thought to contribute to the high forces acting about the shoulder at this point in the throwing cycle, which is especially true for amateur cricketers. The findings of this study were distributed to the medical and conditioning professionals within the Cricket South Africa pipeline, using an educational infographic (Figure 8.3).

Notably, the demands placed on a cricketer when fielding during matches, often require throws to be performed from an unbalanced position. Consequently, a comparison of overhead throwing biomechanics between a stationary position and run-up approach was investigated (Chapter 6). Throwing with a run-up further amplified the potential risk for shoulder injury at MER. This approach was found to approximately double the forces exerted on the shoulder at MER, as a result of the greater dominant hip and lumbo-pelvic flexion demonstrated by these cricketers.

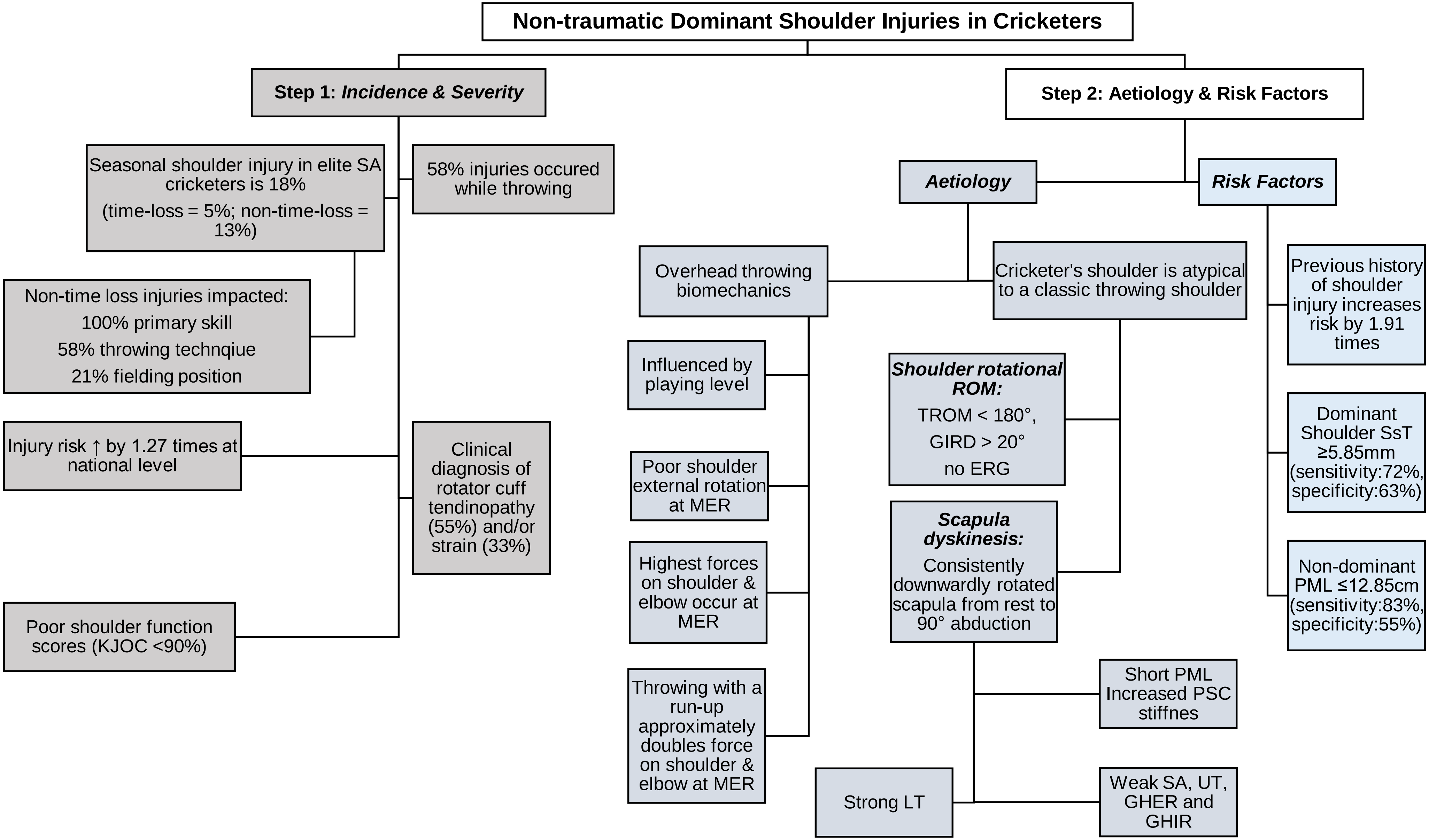

Figure 8.1: Shoulder injuries in cricketer's represented as the first two steps in van Mechelen's sports injury research model[26]

The findings of Part 1 and 2, most particularly the increased GIRD described in these cohorts of cricketers, prompted Part 3 of this thesis in which the association between the musculoskeletal profile of a cricketer's shoulder and overhead throwing biomechanics, was investigated (Chapter 7). As the cricketer's shoulder did not demonstrate the traditional *"thrower's paradox"*, GIRD was selected as the musculoskeletal variable of choice. A smaller base of support during the preparatory phase of throwing from a stationary position as well as a reduction in dominant hip internal rotation ROM during the deceleration phase of both throwing approaches was associated with GIRD. It is believed that cricketers actively engage the dominant hip internal rotators, to obtain early forward pelvic rotation which may facilitate the lumbo-pelvic flexion utilised to throw overhead. The latter increases the posterior shoulder force required to optimally decelerate the throwing arm and is achieved by increasing shoulder horizontal adduction ROM. This eccentrically loads the PSC and may contribute to the development of GIRD. Consequently, cricketers may be at increased risk for injury to the rotator cuff and GH labrum.[10].

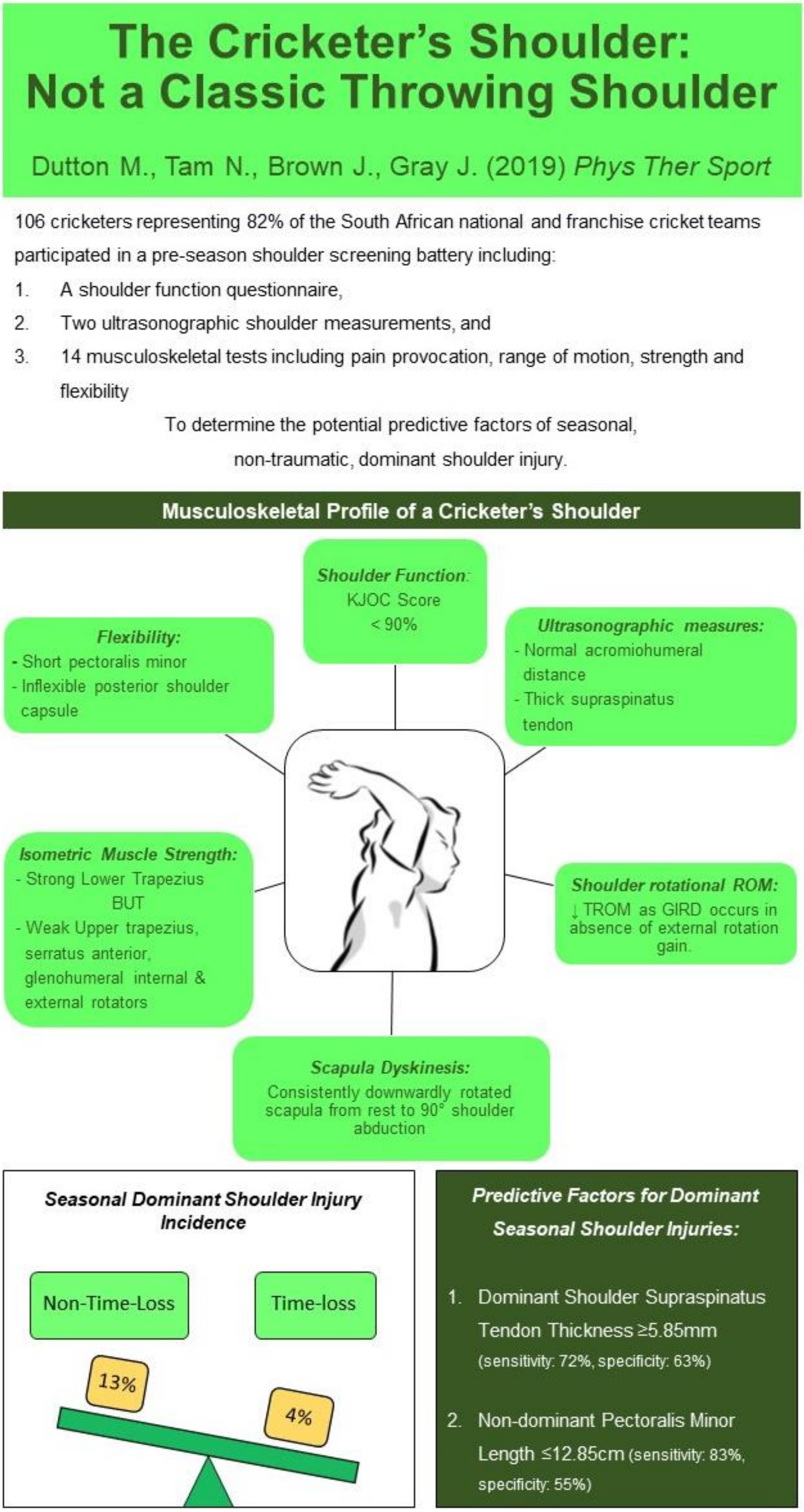

Figure 8.2: An infographic representing the findings of Part 1: Risk factors for shoulder injury

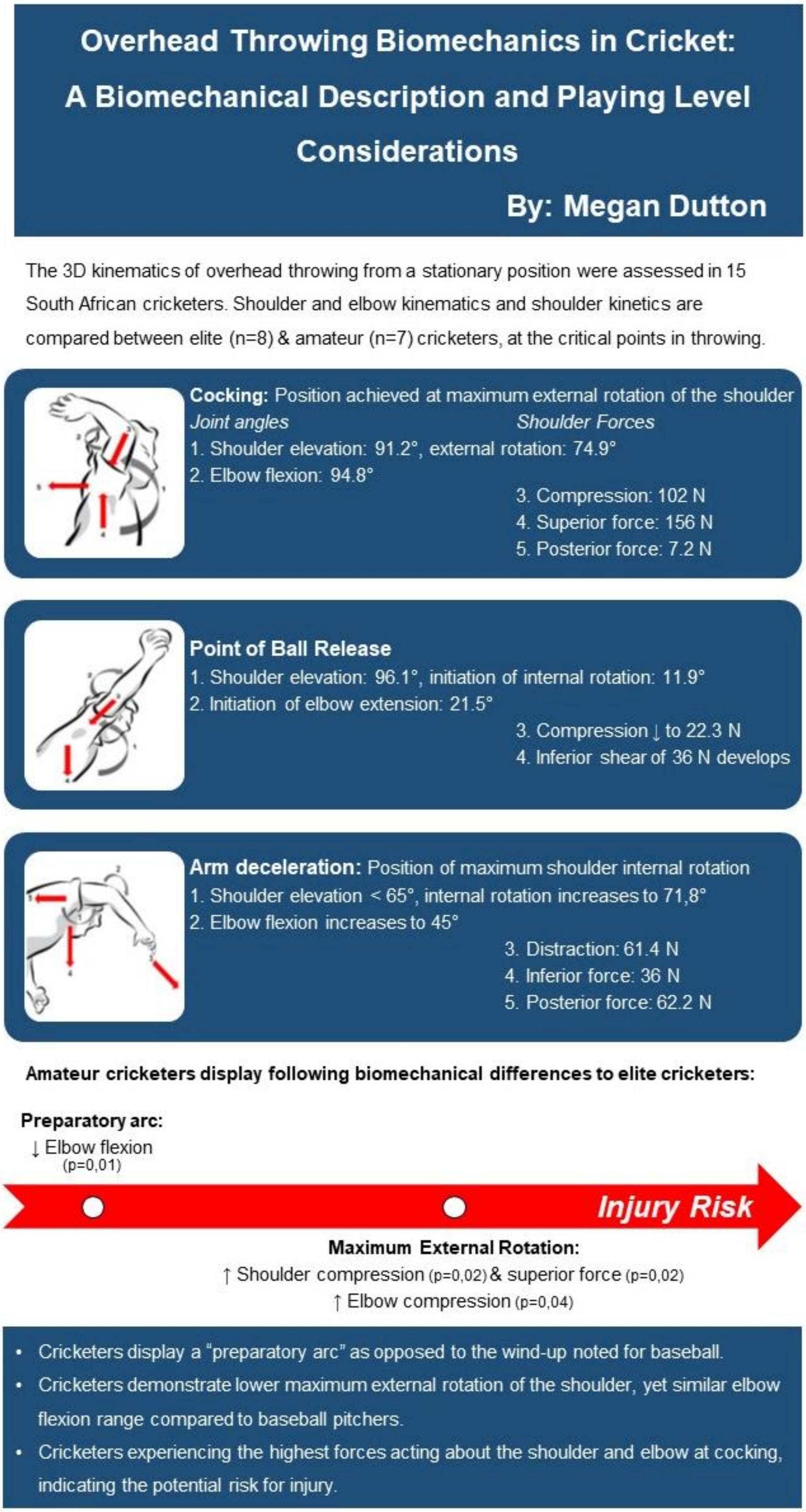

Figure 8.3: An infographic detailing the findings of Chapter 5: Overhead throwing biomechanics in cricket: A biomechanical description and playing level considerations.

8.2 FUTURE RESEARCH RECOMMENDATIONS

Future long-term injury surveillance studies should consider using the *"medical attention"* injury definition proposed in the updated international consensus statement on injury surveillance in cricket,[134] as well as a measure of function, when determining shoulder injury incidence. This will enable a realistic representation of both traumatic and non-traumatic injuries between shoulders. Further, knowledge of the nature (first incident, recurrent, chronic) and activity associated with injury; as well as the impact of injury on primary skill, throwing technique and fielding position, will be enhanced.

The pre-season shoulder screening protocol utilised in this thesis, included a variety of tests with good inter- and intra-rater reliability, previously used in research in overhead athletes. However, it is recommended that this pre-season shoulder screening protocol should be validated, according to Bahr's (2016)[198] recommendations. This will require the protocol to be implemented in multiple cricketing cohorts performing at similar levels across the world. Further, as Part 1 of this study was conducted on the majority of the cohort of cricketers participating at elite level in South Africa, a multi-centre approach may improve statistical power and allow for player speciality/position comparisons with shoulder injury risk. In addition, the efficacy of the pre-season shoulder screening protocol in association with targeted injury prevention programmes, requires investigation. This should be conducted after the validation process using randomised controlled trials.[26,198] These suggested studies will facilitate the completion of van Mechelen's injury prevention model.[26]

Further research in the area of overhead throwing biomechanics employed by cricketers is necessary. Motion analysis studies should consider the kinematic and kinetic effect of overhead throwing from a stationary position and run-up approach, on performance parameters such as ball velocity and throwing accuracy. In addition, the kinematic measurement of horizontal adduction and the associated impact on shoulder and elbow forces experienced during arm deceleration needs to be determined. Further, motion analysis studies conducted on cricket throwing need to be broadened to include different throwing techniques, such as the side-arm and sub-marine throw; and different throwing approaches utilised by cricketers when fielding, e.g. chasing after a ball to collect it, turn and throw. This will facilitate comparison between cricketer's performance in the field during matches and throwing biomechanics. In addition, the association of other shoulder specific musculoskeletal variables inherent to a cricketer's shoulder, such as scapula dyskinesis and global weakness of the GH internal and external rotators, on overhead throwing performance requires investigation. Finally, the efficacy of a rehabilitation program to address the specific ROM and strength deficits of a cricketer's shoulder on throwing technique and shoulder stress should be determined, and compared, to coaching of effective throwing technique.

These findings will further aid the understanding of shoulder injury aetiology when throwing overhead in cricket. Ultimately, the proposed studies will contribute to a cricket specific shoulder conditioning program that incorporates the entire kinetic chain. The global implementation of such a program will reduce the overall injury risk and incidence and in all likelihood improve cricket performance.

8.3 CLINICAL AND PRACTICAL IMPLICATIONS

This PhD research highlights the incidence of shoulder injuries, aspects of throwing technique, and musculoskeletal risk factors associated with injury among elite South African cricketers. These findings indicate that a substantial proportion of shoulder injuries are non-time-loss, which influence primary skill and fielding ability. Additionally, these findings provide clinicians working in cricket with a shoulder specific musculoskeletal screening protocol, providing a potential focus for injury prevention strategies. These strategies could incorporate the monitoring of throwing load during both training and matches; as well as the development of shoulder specific rehabilitation protocols, similar to the super six exercises developed as a by-product of this research in collaboration with Cricket South Africa (Figure 8.4). This program was developed specifically for "grass-root" development cricketers, who do not necessarily have access to appropriate rehabilitation facilities and/or equipment. The exercises incorporated into this program have been shown to demonstrate the most optimal recruitment of the scapula stabiliser and rotator cuff muscles,[160,176] found to be generally weak within this thesis. In addition, a stretch of the posterior shoulder capsule was included to reduce the development and impact of GIRD on the overhead throwing shoulder.[12,13] These super 6 exercises will be adapted for elite level cricketers with the addition of an advanced preventative program for the shoulder, in future.

Further, this PhD thesis provides a thorough description, insight and initial understanding of overhead throwing biomechanics in cricketers. These findings highlight the importance of assessing the entire kinetic chain when cricketers present with shoulder injury. Clinicians should be cognisant of the impact of hip strength and flexibility; and approach used, when cricketers throw overhead. Consequently, shoulder rehabilitation programs should include both hip abduction strengthening and rotational flexibility exercises. Further, cricketers with shoulder injury may be advised to field in the inner ring,[31] attempt to throw with a run-up and adopt a more side-arm throwing technique. These adaptations are thought to aid in reducing the velocity required to throw and resultant workload on the shoulder. Finally, in an attempt to prevent the development of potentially injurious ROM and strength deficits, good throwing coaching at all levels of play is highly recommended.

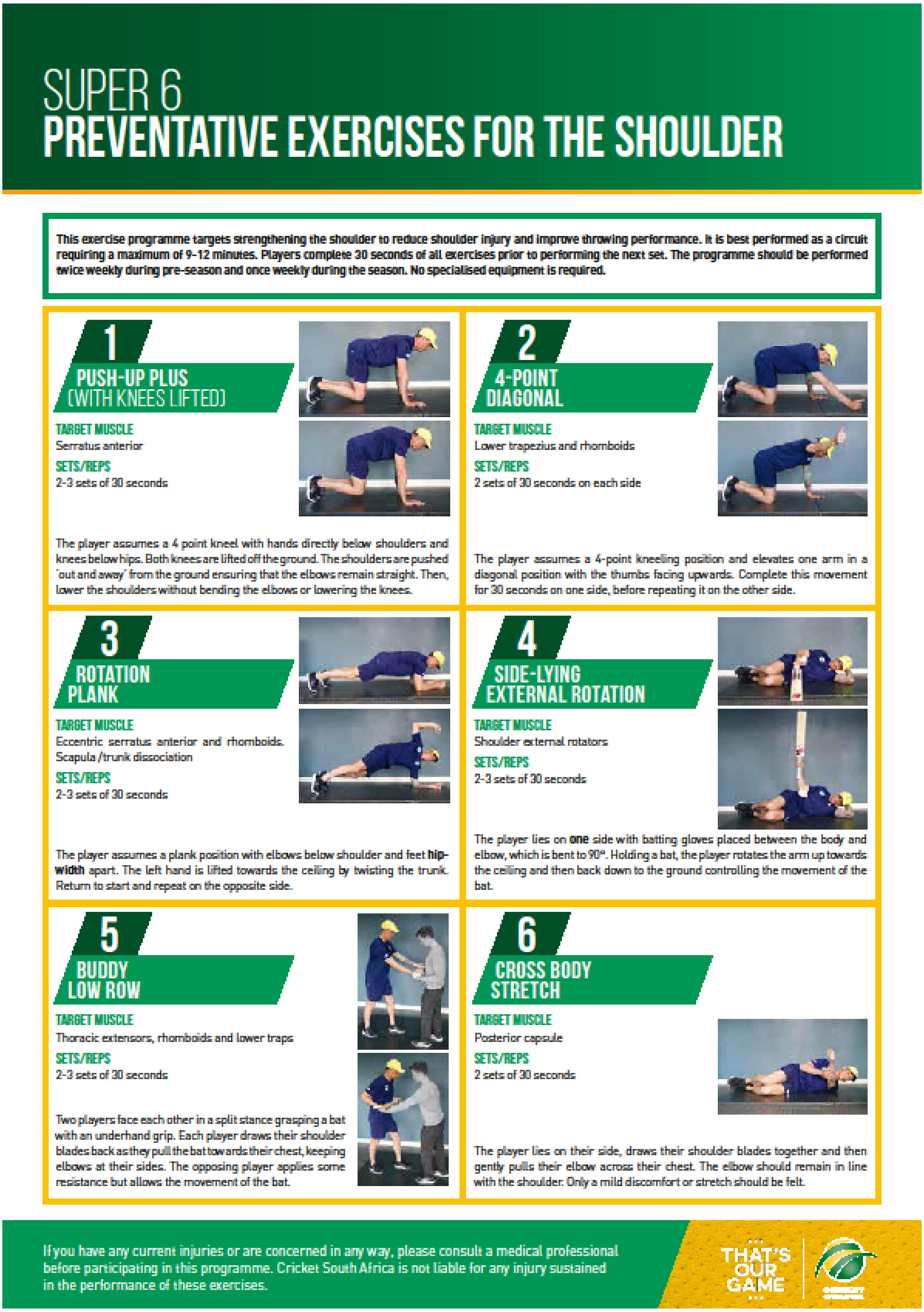

Figure 8.4: The super 6 preventative exercises for the shoulder, developed in collaboration with Cricket South Africa.

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APPENDIX I: KERLAN-JOBE ORTHOPAEDIC CLINIC SHOULDER AND ELBOW (KJOC) SCORE

Subject Code:_______________

<u>Please answer the following questions related to your history of injuries to YOUR ARM ONLY:</u>

1. Is your arm currently injured? YES NO
2. Are you currently active in your sport? YES NO
3. Have you missed game or practice time in the last year due to an injury to your shoulder or elbow? YES NO
4. Have you been diagnosed with an injury to your shoulder or elbow other than a strain or sprain? YES NO
5. Have you received treatment for an injury to your shoulder or elbow? YES NO

   If yes, what was the treatment? (Check all that apply)

   - ☐ Rest
   - ☐ Therapy
   - ☐ Surgery (please describe)________________________

<u>Please describe your level of competition in your current sport:</u> (Use Protea, Franchise, Club, High school as choices)

6. What is the highest level of competition you've participated at? __________________
7. What is your current level of competition? ___________________________________
8. If your current level of competition is not the same as your highest level, do you feel it is due to an injury to your arm? YES NO

Please check ONE category only that best describes your current status:

- ☐ Playing without any arm trouble
- ☐ Playing, but with arm trouble
- ☐ Not playing due to arm trouble

Instructions to athletes:

The following questions concern your physical functioning during game and practice conditions. Unless otherwise specified, all questions relate to your shoulder or elbow. Please answer with an X along the horizontal line that corresponds to your current level.

1. How difficult is it for you to get loose or warm prior to competition or practice?

←――――――――――――――――――――――――――――――――――――→

Never feel loose during games or practice *Normal warm-up time*

2. How much pain do you experience in your shoulder or elbow?

←――――――――――――――――――――――――――――――――――――→

Pain at rest *No pain with competition*

3. How much weakness and/or fatigue (i.e.: loss of strength) do you experience in your shoulder or elbow?

←――――――――――――――――――――――――――――――――――――→

Weakness or fatigue preventing any competition *No weakness, normal competition fatigue*

4. How unstable does your shoulder or elbow feel during competition?

←――――――――――――――――――――――――――――――――――――→

"Popping out" routinely *No instability*

5. How much have arm problems affected your relationship with your coaches, management and agents?

←――――――――――――――――――――――――――――――――――――→

Left team, traded or waived, lost contract or scholarship *Not at all*

The following questions refer to your level of competition in your sport. Please answer with an X along the horizontal line that corresponds to your current level.

6. How much have you had to change your throwing motion due to your arm?

⟷

Completely changed, don't perform motion anymore *No change in motion*

7. How much has your velocity and/or power suffered due to your arm?

⟷

Lost all power, became finesse or distance athlete *No change in velocity/power*

8. What limitation do you have in endurance in competition due to your arm?

⟷

Significant limitation (stopped bowling or changed field placing) *No endurance limitation in competition*

9. How much has your control (bowling, throwing) suffered due to your arm?

⟷

Unpredictable control *No loss of control*

10. How much do you feel your arm affects your current level of competition in your sport (i.e.: is your arm holding you back from being at your full potential)?

⟷

Cannot compete, has to switch sports *Desired level of competition*

APPENDIX II: GENERAL METHODOLOGY FOR THE IDENTIFICATION OF RISK FACTORS CONTRIBUTING TO SHOULDER INJURY IN CRICKETERS

I. INTRODUCTION

Appendix two describes the methods and procedures used in the pre-season screening and shoulder injury risk studies discussed in Chapters 3 and 4. Prior to the commencement of the study, ethical approval was obtained from the Cricket South Africa Research Committee and the Human Research Ethics Committee, Faculty of Health Sciences, University of Cape Town (HREC 364/2016) (Appendix VI). In addition, eligible participants completed informed consent forms (Appendix VII) following the provision of verbal and written information detailing the study.

II. PARTICIPANT INFORMATION

II.I Recruitment

At their pre-season musculoskeletal screening, all cricketers representing a South African cricket franchise team during the 2016/2017 season were invited to participate in this study. A total of 106 participants were voluntarily recruited from various squads including the Proteas (National Cricket South Africa Team), Nashua Titans (Centurion, Gauteng), Highveld Lions (Johannesburg, Gauteng), Sunfoil Dolphins (Kwa-Zulu Natal), Chevrolet Warriors (Eastern Cape), Chevrolet Knights (Bloemfontein) and Nashua Cape Cobras (Western Cape).

II.II Inclusion and Exclusion Criteria

Participants were eligible to participate in this study if they were 18 years of age or older and formed part of the respective franchise squads for the 2016/2017 cricket season. Participants were expected to perform at least two cricket specific (net), one fielding training and one to two fitness sessions per week. In addition, participants were expected to play in at least one format (Four day, One day or T20) of cricket match during the 2016/2017 season.

II.III Sample Size Determination

Data from previous studies which measured the effect of shoulder pain on scapula upward rotation,[7,86] glenohumeral (GH) internal and external rotation ROM,[32] strength of scapula stabilisers (serratus anterior)[113] and strength of GH internal and external rotators was used to ensure that the sample size would provide sufficient statistical power. Strength of GH internal and external rotators was selected to determine sample size, as this measurement required the largest sample size to obtain a significant statistical power for this study. Required sample size for strength of GH internal and external rotators was calculated using a small meaningful difference of 2, and a standard deviation of 3 (effect size $d = 0.7$). With statistical significance accepted as $p < 0.05$, a group of 29 participants will provide 80% statistical power for strength of GH internal and external rotators, respectively.

III STUDY PROCEDURE

This study was approved by the Cricket South Africa Research Committee and formed part of the routine musculoskeletal screening protocols that are conducted on all franchise cricket players as standard procedures in the pre-season.

III.I Informed Consent

Eligible participants were required to complete an informed consent form prior to the conduction of this study (Appendix VII). The informed consent form stated that ethical approval for this study had been granted and that participation in the study was voluntary. The testing procedures and the risk, benefits and significance of the study were thoroughly explained. The participants were informed of the right to withdraw from the study at any time and that confidentiality would be maintained throughout the study. In addition, the participant's decision to participate in the study remained undisclosed to their respective coaching and/or management staff; and did not compromise their selection for representation within their respective teams in any way or form.

III.II Demographic Information

Participants were required to complete a questionnaire to obtain demographic data, training and competition history and injury history (Appendix V). This information was obtained from each participant at the time of screening.

III.III Anthropometric Measurements

All participants had their body composition assessed during the pre-season fitness screening conducted by the respective franchise biokineticist/trainer. Mass, stature and skin-fold measurements were recorded. Body fat was expressed as a percentage of body mass. These measurements were provided by the CSA trainers for each participant.

IV. PRE-SEASON SHOULDER SCREENING

The pre-season shoulder screening protocol was conducted concurrently with each respective franchise's routine pre-season musculoskeletal screening. The shoulder screening included a questionnaire (which was also completed at the end of the 2016/2017 season), a battery of 12 shoulder specific and three hip specific tests and two ultrasonographic measurements of the shoulder.

IV.I Kerlan-Jobe Orthopaedic Clinic Shoulder and Elbow Score

Shoulder function was assessed using the Kerlan-Jobe Orthopaedic Clinic (KJOC) Shoulder and Elbow Score. This self-report measure consists of a 100-point scale, divided into three sections including function and athletic performance (four questions), symptoms related to the upper limb (five questions) and interpersonal relationships related to performance (one question) (Appendix I). Each question is measured using a visual analogue scale (VAS) where the extreme left indicates lowest level of function or performance and greatest severity of the symptom assessed. The extreme right of the VAS scale represents the highest level of function or performance and lowest possible severity of symptom assessed. The KJOC Shoulder and Elbow Score was completed by participants at the pre-season screening, as well as at the completion of the 2016/2017 season.

Alberta et al (2010)[131] found the KJOC Score to be both a reliable (ICC = 0.88) and valid (0.84-0.86) measure of shoulder and elbow function in overhead athletes.

IV.II Pain Provocation Tests

a. Hawkin's-Kennedy Test

The participant was seated on a stool with his feet supported firmly on the ground. The examiner stabilized the scapula of the shoulder to be tested, by applying gentle downward pressure with the hand. The participant's arm was then draped over the examiner's arm. The examiner then performed passive GH internal rotation with the participant's arm positioned in 90° GH abduction and 90° GH flexion,[76] as illustrated in Figure V.I. The participant confirmed the presence of pain with a yes/no answer.

The non-dominant arm was tested prior to testing the dominant arm. A single test per arm was performed and the participant's pain response was noted. This test has a sensitivity of 79% and a specificity of 59%.[165]

Figure II.I: Hawkin's/Kennedy Test performed in 90° glenohumeral abduction (left) and 90° glenohumeral flexion (right).

b. Jobe's and Full Can Tests

The participant was seated on a stool with his feet firmly supported on the ground. Both of the participant's arms were positioned at 90° GH elevation, in the scapula plane and full GH internal rotation (empty can position). The examiner applied downward force resisting further GH flexion, to both of the participant's arms simultaneously.[76]. The participant confirmed the presence of pain with a yes/no answer. The test was repeated using the same protocol described above, however the participant's arms were positioned at 90° GH elevation, in the scapula plane and 90° GH external rotation (full can position). Jobe's test, in conjunction with the full can component (Figure V.II), was performed once and the participant's pain response and affected arm were recorded. Due to the limited evidence for the sensitivity, specificity and accuracy of this test, it was interpreted in combination with the other impingement tests.[165]

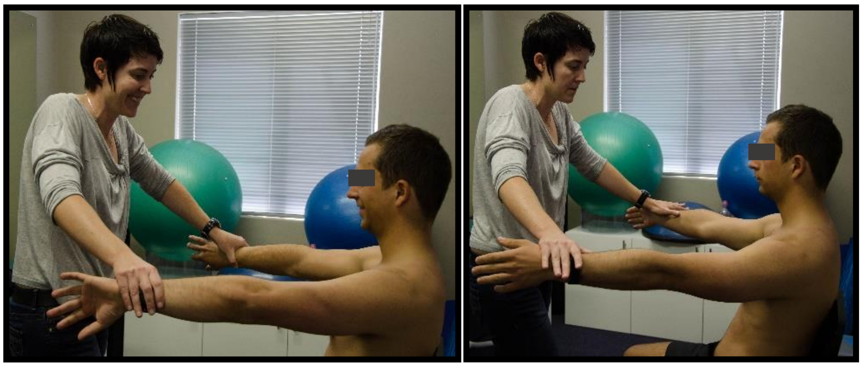

Figure II.II: The Jobe (left) and Full Can (right) Tests.

IV.III Joint Range of Motion

a. Passive glenohumeral internal and external rotation

The range of glenohumeral internal and external rotation was measured using an inclinometer (Digi-Pas DWL80E, Digipas Technologies, Inc., Dundee, England). Cools et al (2014)[173] found the intrarater reliability for the inclinometric measurements of passive GH rotational range of motion to be excellent (ICC = 0.89-0.99) and recommended rotational ROM be measured in supine.

Glenohumeral rotation range of motion was measured in supine, using the protocol described by Kolber et al (2012)[172] and illustrated in Figure V.III. The participant was positioned with the shoulder at 90° abduction, elbow flexed to 90°, neutral forearm rotation and wrist in neutral. A towel roll was placed under the upper arm to ensure neutral horizontal positioning. The inclinometer was placed on dorsal aspect of the forearm, just proximal to the wrist, and set at 0° vertically. The examiner then passively moved the participant's forearm so that the hand was orientated in a thumb down position for external rotation and thumb up position for internal rotation, without pain. The left and right shoulders were measured twice and the average measurement was recorded.

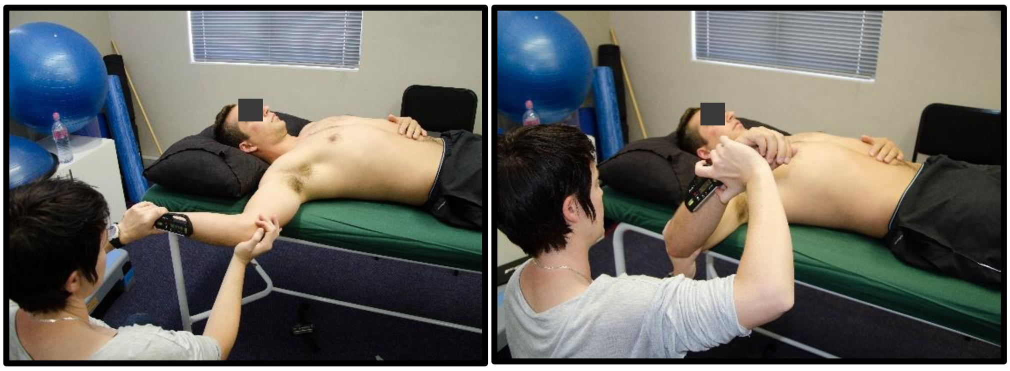

Figure II.III: Passive GH external (left) and internal (right) rotation ROM measured using an inclinometer.

b. Upward scapula rotation

Upward scapula rotation was measured using the protocol originally described by Johnson et al (2001)[170] and modified by Watson et al (2005).[171] Participants were instructed to stand comfortably with their feet positioned shoulder width apart, arms by side and elbows extended. An inclinometer was secured perpendicularly to the shaft of the humerus, just above the lateral epicondyle using a Velcro strap. The inclinometer was set at 0° vertically, i.e.: perpendicular to the floor. The actual resting position of the participants' humerus, relative to vertical was recorded.

Participants were then instructed to abduct their arm in the scapula plane and asked to stop at 45°, 90° and 135° (Figure V.IV). Scapula upward rotation was measured at rest, and at each of these abduction positions by aligning the base of a second inclinometer to the spine of the scapula, manually. Previous studies have performed multiple measures of this test.[170,171] Therefore, an average of two measurements for each of the dominant and non-dominant shoulders respectively, were recorded. This method of assessing scapula upward rotation has demonstrated good to excellent intrarater reliability (ICC = 0.89 – 0.96) and good validity.[170]

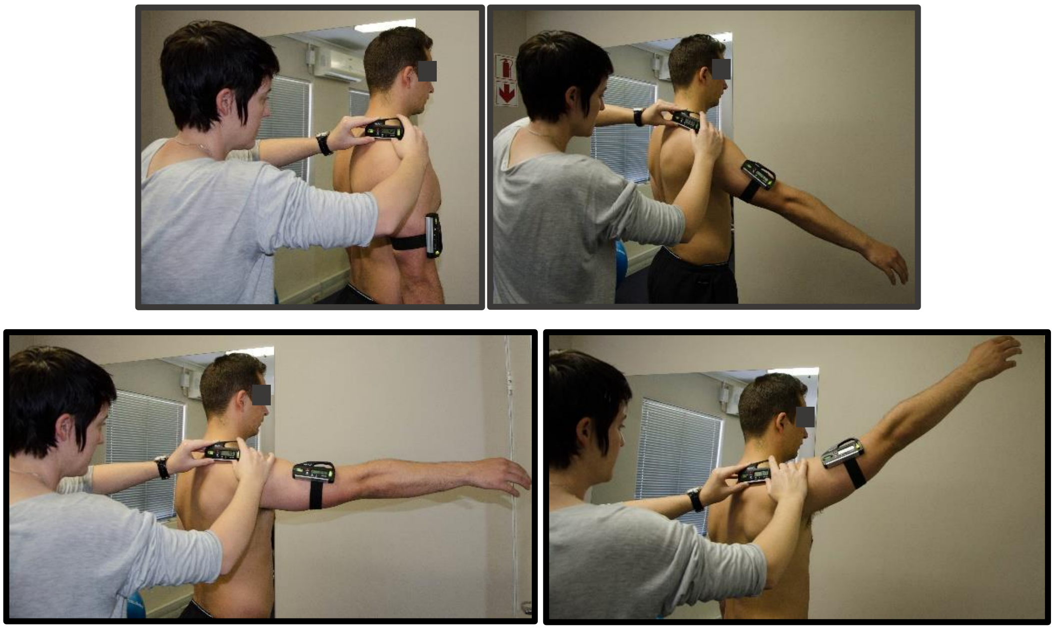

Figure II.IV: The measurement of upward scapula rotation at 0° (top left), 45° (top right), 90° (bottom left) and 135° (bottom right) GH abduction along the scapula plane.

c. Passive hip internal and external rotation

Passive hip rotation was measured with an inclinometer (Digi-Pas DWL80E, Digipas Technologies, Inc., Dundee, England) in supine, using the method described by Gabbe et al (2004).[174] This position was selected as the reliability of measuring hip rotation in prone has been demonstrated to be poor by Dennis et al (2008)[199]. Further, excellent intra- and inter-reliability for this measurement has been demonstrated by Gabbe et al (2004)[174] and Pua et al (2008).[175]

The participant was positioned in supine, with the hip to be tested in neutral rotation and lower leg hanging off the side of the treatment table. The contralateral leg was flexed at the hip and knee, so that the contralateral foot was placed on the treatment table.

The examiner passively rotated the hip into internal rotation, by moving the foot of the tested hip laterally, away from the participant's midline, whereas external rotation was measured by passively moving the foot across the participant's midline. Passive movement was measured at the end of available hip rotation without eliciting movement at the pelvis. The inclinometer was placed along the shaft of the tibia, 5 cm distal to the tibial tuberosity. Prior to each measurement, the inclinometer was zeroed with the hip maintained in neutral rotation. An average of two measurements were recorded for internal and external rotation respectively. In addition, both hips were measured. Figure V.V demonstrates the measurement position for passive hip rotation ROM.

Figure II.V: Inclinometric measurement of passive hip external (left) and internal (right) rotation ROM.

IV.IV Isometric Muscle Strength

Isometric muscular strength was measured using a hand-held dynamometer (HHD) (MicroFET 2 hand held dynamometer, Hoggan Scientific, LCC., Salt Lake City, Utah, USA). Hayes et al (2002)[168] found the intrarater reliability to be good for GH internal rotation (ICC = 0.64 – 0.96) and excellent for GH external rotation (ICC = 0.78 – 0.98). Further, Tyler et al (2005)[167] found the intrarater reliability of HHD for all shoulder movements to be excellent (ICC = 0.79 – 0.96). In addition, hand-held dynamometry has been shown to be a valid measure of isometric shoulder strength.[200]

Each participant performed three repetitions at 70% of maximum voluntary contraction of isometric serratus anterior, upper and lower trapezius muscle contraction and GH internal and external rotation, respectively. This was done following the completion of the KJOC questionnaire, in order to familiarize the participants with the strength testing component of the screening protocol and warm up their respective shoulders prior to testing.

a. **Glenohumeral Internal and external rotators**

Glenohumeral internal and external rotator strength (Figure V.VI) was measured in a seated 90-90 position i.e. 90° of GH abduction, 90° of GH external rotation and 90° elbow flexion, as described by Hayes et al (2002).[168] External rotation strength was measured by the investigator stabilizing the medial aspect of the distal humerus with the non-testing hand, and the HHD centred on the dorsal aspect of the distal forearm. For internal rotation strength, a similar protocol was used, however the investigator stabilized the lateral aspect of the distal humerus and the HHD was centred on the volar aspect of the forearm.

Participants were instructed to hold the testing position of the extremity as the investigator applied manual force to the participants' limb until the maximal muscular effort was overcome. Each measurement was repeated twice on both the left and right arms and an average recorded.

Figure II.VI: Isometric muscle strength of glenonhumeral external (left) and internal rotators, using a hand held dynamometer.

b. **Scapula stabilisers**

The scapula stabilizer muscle strength of the serratus anterior and lower trapezius was measured, as described by Donatelli et al (2000).[128] Upper trapezius strength was assessed according to the protocol used by Hislop et al (1995).[166] Cools et al (2010)[113] used these techniques (Figure V.VII) to describe the scapulothoracic position, strength and flexibility in adolescent tennis players. An average of two measurements per muscle tested for each shoulder respectively was recorded.

i. Serratus Anterior

Serratus anterior muscle strength was measured in supine with the arm positioned in 90° of forward flexion and elbow fully extended, as shown in Figure 4.7. The HHD was placed in the participant's palm of the arm being tested. A downward force was applied by the investigator to the participant's palm. The participant was instructed to perform scapula protraction.

ii. Upper Trapezius

Upper trapezius muscle strength was measured in sitting with the arm positioned comfortably by the participant's side. The investigator stood behind the participant and placed the HHD over the superior aspect of the scapula. The participant was instructed to elevate the scapula towards the ceiling, while the investigator applied a downward force to the HHD.

iii. Lower Trapezius

Lower trapezius muscle strength was measured with the participant in prone and the shoulder elevated to 145° of abduction and full external rotation (i.e.: thumbs up position). The investigator stood on the side of the arm being tested. The HHD was placed over the distal 1/3 of the lateral aspect of the participant's radius. Participants were instructed to lift their arm up towards the ceiling, while the investigator applied a downward force (perpendicular to the floor) to the HHD.

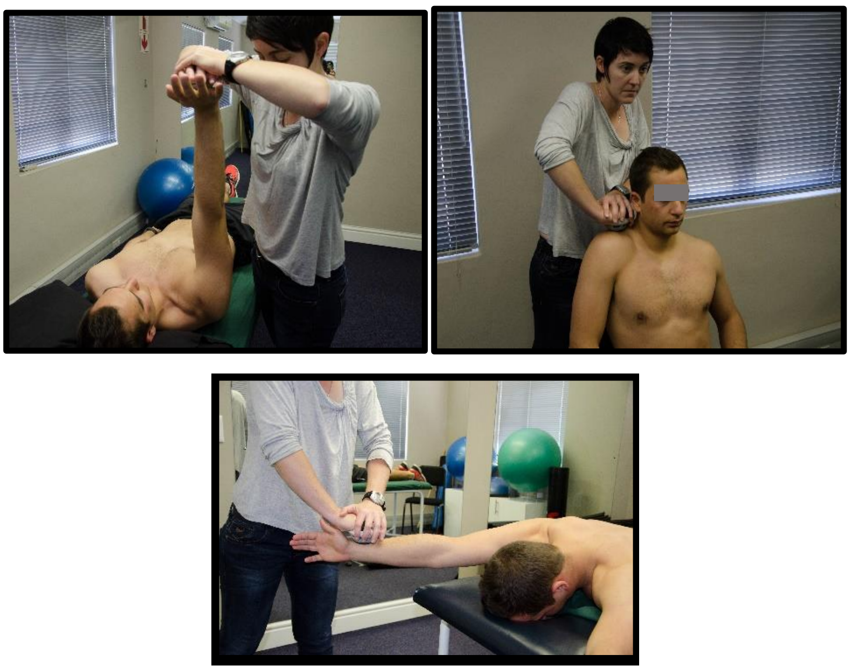

Figure II.VII: Dynamometric isometric testing of the serratus anterior (top left), upper trapezius (top right) and lower trapezius (bottom) muscles.

c. Gluteus Medius Muscle

Gluteus medius muscle strength was measured in side lying, as described by Widler, et al (2009)[169] and is illustrated in Figure V.VIII. Participants were positioned squarely, lying on their left side. The left knee and hip was flexed to 30°for stability and comfort, with both arms crossed over the chest comfortably. The right leg was abducted to 10° in neutral rotation, passively. Participants were asked to hold this position with full knee extension. The HHD was placed 5 cm proximal to the lateral femoral epicondyle. Participants were then instructed to perform a maximum voluntary contraction against the downward force applied by the investigator through the HHD. At no point was the allowed participant to make use of their upper extremities to stabilize the trunk. The non-dominant leg was measured prior to the dominant leg.

Each leg was measured twice and an average measurement for isometric gluteus medius strength was recorded. Good intra-rater reliability (ICC = 0.90) and construct validity has been established for this method of measuring isometric gluteus medius muscle strength.[169]

Figure II.VIII: The isometric strength measurement of the gluteus medius muscle, with a hand-held dynamometer.

VI.V Flexibility

a. Pectoralis Minor Muscle

Pectoralis minor muscle length was measured according to the protocol described by Borstad (2008)[158] and illustrated good validity. This method has been adapted by Cools et al (2010)[113] to a supine position.

Participants were positioned in supine with the arms placed comfortably next to their torso in neutral shoulder rotation and elbow extension. Two anatomical landmarks were identified and marked using a skin pencil. These landmarks included the medial-inferior angle of the coracoid process and the lateral aspect of the sternocostal joint of the inferior aspect of the fourth rib.

A calliper (Mastercraft Vernier Calliper, Mastercraft Tools, Johannesburg, South Africa) was used to measure the distance between the two anatomical landmarks (Figure V.IX). The participant's non-dominant arm was measured first, followed by the dominant arm. Each measurement was repeated twice and an average was recorded.

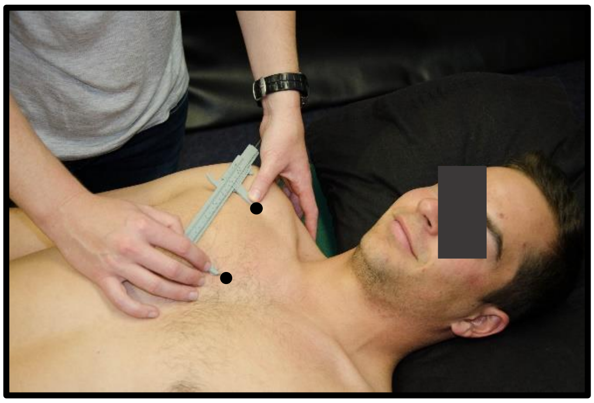

Figure II.IX: The measurement of pectoralis minor muscle length using a calliper.

b. Posterior Shoulder Complex

Posterior shoulder tightness was measured using the supine method described by Laudner et al (2006).[99]. Good intrarater reliability (ICC = 0.91) and construct validity have been established for this method of testing posterior shoulder tightness.[155]

Figure V.X illustrates the positioning of participants for their measurement of posterior shoulder tightness. Participants were positioned in supine, with their arms by side in neutral shoulder rotation and full elbow extension. An inclinometer (Digi-Pas DWL80E, Digipas Technologies, Inc., Dundee, England) was secured to the arm and placed perpendicular to the shaft of the humerus, just above the lateral epicondyle using a Velcro strap.

The participant was instructed to elevate their arm to 90° forward flexion with 90° elbow flexion. Here the inclinometer was set at 0° to the vertical. Thereafter, participants were instructed to maximally retract their scapula, which was stabilized by the thenar eminence of the investigator, against the lateral border of the scapula. This ensured that the scapula was stabilized in a maximally retracted position. The investigator then passively horizontally adducted the humerus to end range of motion, maintaining neutral rotation. The inclinometer measurement was noted. Each arm was measured three times, with an average measurement for posterior shoulder tightness recorded. The non-dominant arm was measured prior to the dominant arm.

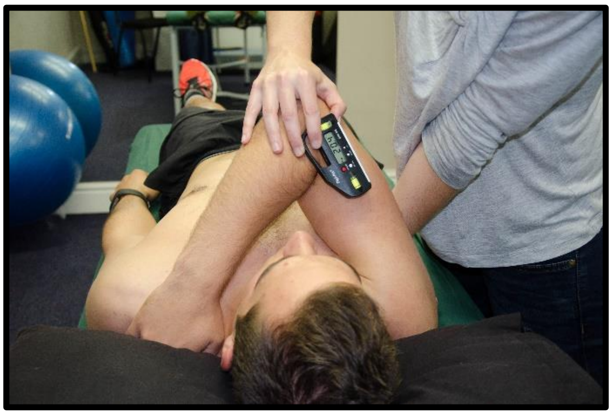

Figure II.X: Posterior shoulder complex measurement using an inclinometer.

IV.VI Ultrasonographic Measurements

Ultrasonographic measurement (M7 Diagnostic Ultrasound System, Shenzen Mindray Bio-medical electronics Co., Ltd., Guangdong, China) of the acromiohumeral distance (AHD) and supraspinatus tendon thickness (SsT) was measured using the protocol described by McCreesh et al (2015).[126] Excellent intra-rater reliability for AHD measurement (ICC = 0.92) and supraspinatus tendon thickness (ICC = 0.93) has been determined.[126]

Participants were positioned in sitting with the measured arm by their side, elbow bent to 90° and hand resting on their lap for AHD measurement; and with their palm on their iliac crest with elbow pointed posteriorly for SsT measurement respectively. This positioning is shown in Figure V.XI. Both the dominant and non-dominant shoulders were measured.

Figure II.XI: Participant and ultrasound transducer positioning for the measurement of the acromiohumeral distance (left) and supraspinatus tendon thickness (right).

a. Acromiohumeral Distance

Acromiohumeral distance was measured by placing the ultrasound transducer longitudinally along the centre of the acromion. Once the acromion and humerus were visualized, the transducer was moved forward until the anterior aspect of the acromion and concurrent view of the humeral head was located. This image was captured and the shortest distance between the inferolateral edge of the anterior acromion and the humeral head was measured (see Figure V.XII).

b. Supraspinatus Tendon Thickness

Supraspinatus tendon thickness was measured in the transverse plane. The ultrasound transducer was placed on the acromion and moved laterally to visualize the supraspinatus tendon. Once in view, the transducer was moved anteriorly until the intra-articular portion of the long head of biceps tendon was also in view.

This image was captured and the SsT thickness was measured at 5mm and 10mm posterior to the biceps tendon (see Figure V.XIII). An average of these two measurements was noted.

Figure II.XII: The ultrasonographic measurement of the acromiohumeral distance.

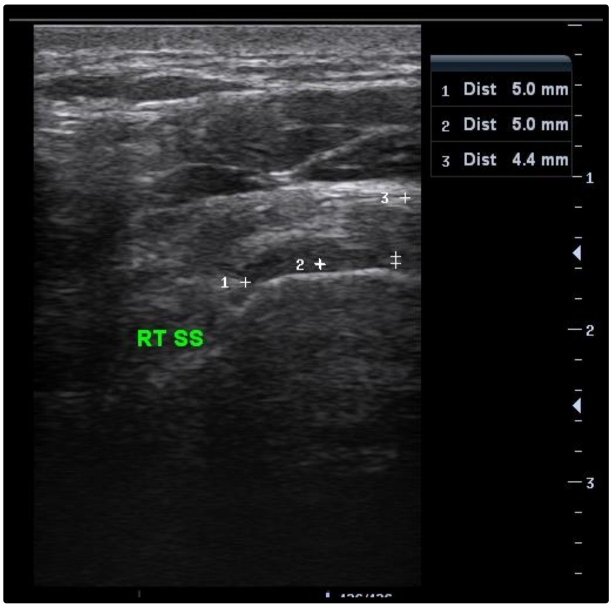

Figure II.XIII: The ultrasonographic measurement of the supraspinatus tendon thickness.

IV.V INJURY SURVELLIENCE

The injuries sustained by participants during the 2016/2017 cricket season were tracked and monitored via the Peformax database. These injuries were recorded on the database by the respective franchise medical personnel who are qualified medical doctors or physiotherapists. Clinical diagnosis of injuries followed the International Statistical Classification of Disease and Related Health Problems (ICD) list, produced by the World Health Organisation.

In addition, the franchise medical personnel were briefed by the principal investigator prior to the start of this study regarding the definition for shoulder pain.

For the purposes of this study, shoulder pain was defined as a physical complaint or manifestation of pain for one day or longer, sustained during competition and/or training, irrespective of the need for medical attention or loss of time to training and/or competition due to the pain.

A spreadsheet of the injury data (Appendix VIII) was requested for the participants in the study. The spreadsheet for each franchise was sent to the franchise physiotherapist to be verified. The data obtained included which shoulder was injured, the clinical diagnosis, the nature of the injury (primary incident, chronic or recurrent), whether the injury had an acute or insidious onset, when the injury occurred (practice, match, other), the activity during which the injury occurred (bowling, batting or fielding) and whether the injury influenced the participant’s ability to bat, bowl and field (including a change in throwing action and fielding position). Lastly, all participants were requested to complete the KJOC questionnaire at the conclusion of the 2016/2017 cricket season.

APPENDIX III: GENERAL METHODOLOGY OF THROWING MOTION ANALYSIS

I. INTRODUCTION

This Chapter describes the methods and procedures used in the throwing motion analysis studies (Chapters 5 to 7). Ethical approval was granted in accordance with the requirements of Cricket South Africa Research Committee and the Human Research Ethics Committee, Faculty of Health Sciences, University of Cape Town (HREC 364/2016) (Appendix VI). Participants were provided with verbal and written information prior to obtaining informed consent (Appendix IV) and commencing with the testing protocol.

II. PARTICIPANT INFORMATION

Twenty-nine cricketers were invited to participate in this study. Five cricketers were withdrawn from the study due to injury (four shoulder injuries and one side strain) and one cricketer was unavailable at the time of testing due to university examinations. The remaining 23 cricketers were assigned by the author to one of the following groups, based on the current level of cricket played:

- Elite: Cricketers who are currently playing at franchise level or higher (N = 12)
- Amateur: Cricketers who are currently playing at 1st class level or lower (N = 11)

III. MOTION ANALYSIS LABORATORY

Throwing data was collected in the biomechanical laboratory at the South African Institute of Sport, using an eight camera Vicon MX motion analysis system (Oxford Metrics Ltd., Oxford, England) at 500 Hz. The capture volume included two force plates AMTI OR6 Series force plates (AMTI Force and Motion Inc., Watertown, Massachusetts, USA) set at 2000Hz and positioned centrally within the capture volume.

Calibration of the cameras and force plates occurred prior to each session of data collection. The cameras were calibrated by moving a wand with three 12mm markers of known distance (Figure VIII.I), in a large figure of eight throughout the capture volume, as per manufacturer recommendations. This calculated and orientated the cameras relative to each other. A residual error of less than 0.20 per camera was considered acceptable during calibration. The global co-ordinate system was set by placing a set square (Figure VIII.II) with four 12 mm markers of known distance on the bottom right hand corner of the first force plate.

Finally the force plates were calibrated by manually pushing the auto zero button located on the front panel of the force plate's amplifier.

Figure III.I: An image of the calibration wand used to calibrate the cameras prior to data collection.

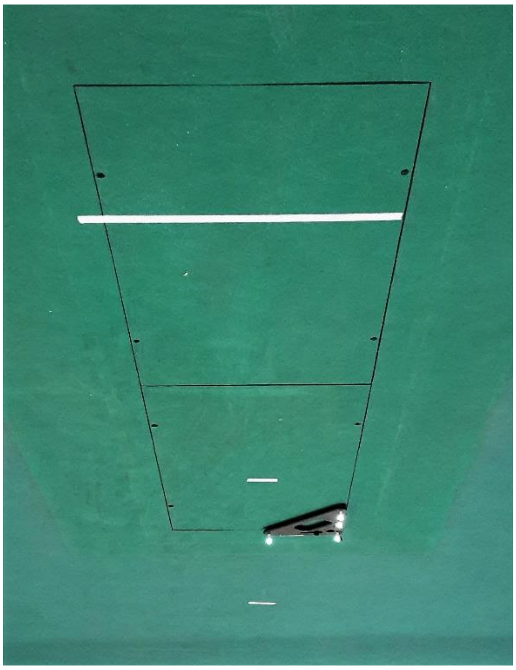

Figure III.II: The set square used to determine the volume origin during camera calibration, is positioned on the bottom right hand corner of the first force plate.

IV. MARKER SET

IV.I Subject Mark-up

A full body marker set was attached to the participant's body using double sided tape (3M, Rivonia, South Africa) and reinforced with hypoallergenic transpore tape (3M, Rivonia, South Africa).

Seventy three retro-reflective markers, consisting of 61 dynamic and 12 static markers were used in the full body marker set (see Figure VIII.III). These markers were attached according to a custom upper body[61] and modified Helen-Hayes lower body[177] marker sets. Markers varied in size from 9mm to 12mm and were either affixed to bony landmarks or comprised of a triad of markers placed on cardboard bases. A detailed description of all marker placements and naming conventions are presented in Tables VIII.I – VII.III.

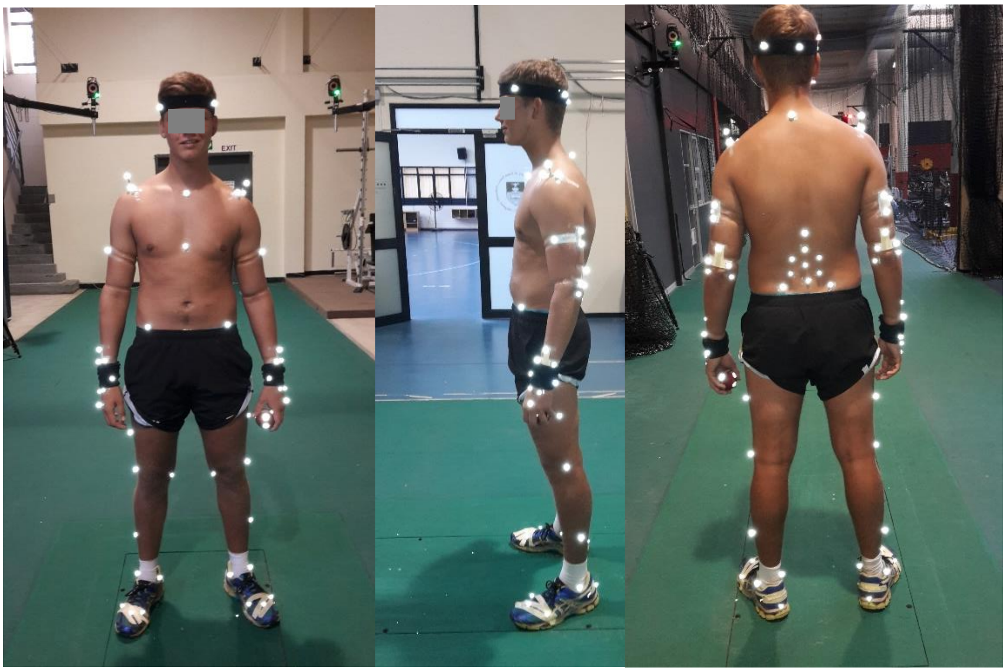

Figure III.III: The full body marker set as viewed from anterior, lateral and posterior.

IV.II Ball Mark-up

Two cricket balls (County Supreme, Liza International, Pakistan) were marked identically using dots cut out of reflective tape (3M, Rivonia, South Africa). Four marker dots were placed along the seam of the cricket ball, with a further two markers placed in the centre on the left and right side of the cricket ball. Finally one additional marker dot was applied to any area of the cricket ball leather, on one side only (Figure VIII.IV).

Figure III.IV: The reflective tape marker dots placed on the cricket balls.

Table III.I: Upper body marker placements and naming conventions.

Segment	Marker	Location
Head	RFHD	Right front head
	LFHD	Left front head
	RBHD	Right back head
	LBHD	Left back head
Thorax	C7	Spinous process of C7 vertebrae
	T10	Spinous process of T10 vertebrae
	CLAV	Sternal notch
	STRN	Xiphisternum
Lumbar Spine	L1	Spinous process of L1 vertebrae
	L3	Spinous process of L3 vertebrae
	L5	Spinous process of L5 vertebrae
	RUL	Right upper lumbar: 5cm to the right of the spinous process of L2 vertebrae
	RLL	Right lower lumbar: 5cm to the right of the spinous process of L4 vertebrae
	LUL	Left upper lumbar: 5cm to the left of the spinous process of L2 vertebrae
	LLL	Left lower lumbar: 5cm to the right of the spinous process of L4 vertebrae
Pelvis	RASI	Right anterior superior iliac crest
	RPSI	Right posterior superior iliac crest
	LASI	Left anterior superior iliac crest
	LPSI	Left posterior superior iliac crest
Right Shoulder	RACR1	Right acromion cluster: anterior
	RACR2	Right acromion cluster: superior
	RACR3	Right acromion cluster: posterior
Left Shoulder	LACR1	Left acromion cluster: anterior
	LACR2	Left acromion cluster: superior
	LACR3	Left acromion cluster: posterior
Right Upper Arm	RUA1	Right upper arm cluster: superior
	RUA2	Right upper arm cluster: anterior
	RUA3	Right upper arm cluster: inferior
Left Upper Arm	LUA1	Left upper arm cluster: superior
	LUA2	Left upper arm cluster: anterior
	LUA3	Left upper arm cluster: inferior
Distal Right Upper Arm	dRUA1	Distal right upper arm cluster: lateral
	dRUA2	Distal right upper arm cluster: superior
	dRUA3	Distal right upper arm cluster: medial
Distal Left Upper Arm	dLUA1	Distal left upper arm cluster: lateral
	dLUA2	Distal left upper arm cluster: superior
	dLUA3	Distal left upper arm cluster: medial

Right Forearm	RFA1	Right forearm cluster: lateral
	RFA2	Right forearm cluster: superior
	RFA3	Right forearm cluster: medial
Left Forearm	LFA1	Left forearm cluster: lateral
	LFA2	Left forearm cluster: superior
	LFA3	Left forearm cluster: medial
Right Hand	RHNC	Right hand dorsal side of the 3rd metacarpophalangeal joint
Left Hand	LHNC	Left hand dorsal side of the 3rd metacarpophalangeal joint

Table III.II: Static calibration marker placements and naming conventions

Segment	Marker	Location
Elbow	RELBM	Right elbow medial epicondyle
	RELBL	Right elbow lateral epicondyle
	LELBM	Left elbow medial epicondyle
	LELBL	Left elbow lateral epicondyle
Wrist	RWRU	Right wrist ulnar side
	RWRR	Right wrist radial side
	LWRU	Left wrist ulnar side
	LWRR	Left wrist radial side
Hand	RHDR	Right dorsal radial carpal
	RHDU	Right dorsal ulnar carpal
	LHDR	Left dorsal radial carpal
	LHDU	Left dorsal ulnar carpal
Ball	Ball 1	Reflective marker dot placed on the lateral (outer) aspect of the ball
	Ball 2	Reflective marker dot placed on the medial (inner) aspect of the ball

Table III.III: Lower body marker placement and naming conventions

Segment	Marker	Location
Upper Leg	RTHI	Right thigh distal third
	LTHI	Left thigh distal third
Knee	RKN	Right knee lateral condyle
	RKNM	Right knee medial condyle
	LKN	Left knee lateral condyle
	LKNM	Left knee medial condyle
Lower Leg	RTIB	Right lateral tibia distal third
	LTIB	Left lateral tibia distal third
Ankle	RANK	Right ankle lateral malleolus
	RANKM	Right ankle medial malleolus
	LANK	Left ankle lateral malleolus
	LANKM	Left ankle medial malleolus
Foot	RHEEL	Right calcaneus
	RTOE	Right dorsal 2nd metatarsophalangeal joint
	RTOEA	Right dorsal 1st metatarsophalangeal joint
	RTOEB	Right dorsal 5th metatarsophalangeal joint
	LHEEL	Left calcaneus
	LTOE	Left dorsal 2nd metatarsophalangeal joint
	LTOEA	Left dorsal 1st metatarsophalangeal joint
	LTOEB	Left dorsal 5th metatarsophalangeal joint

IV.III Subject Calibration

Once all markers were in place a static calibration was performed with the participant standing in the anatomical position and holding the cricket ball in his dominant hand, using a fast bowler's style grip i.e.: Index and middle finger along the seam of the ball which is balanced by the thumb (also on the seam of the ball). The static calibration of a subject permits the joint centres and axes of rotation to be located. In addition the anatomical co-ordinate system can be defined.

V. THROWING TRIALS

V.I Warm-up

Participants were instructed to perform their standard fielding warm-up prior to the assessment of throwing technique. Warm-up will include a series of dynamic stretches to the lower back, upper and lower limbs, followed by a series of four throws per throwing technique, i.e.: overhead, side arm and submarine throws. This will be done to reduce the risk of injury and familiarize the participant to throwing with the full set of reflective markers attached.

V.II Motion Analysis of Throwing

Each participant was required to perform six throws using the overhead, sidearm and submarine throwing techniques respectively. Initially, participants performed six throws of each technique in a stationary position. Thereafter, the participant was positioned five metres away from a series of six beacons, each elevating a cricket ball. Participants were required to run towards the beacon, pick-up the ball and throw towards a set of stumps positioned 40 metres away[1] (Figure VIII.IV). Six throws of a single technique were completed before allowing the participant a rest period of two minutes.[36] This sequence was repeated until each of the three throwing techniques had been completed.

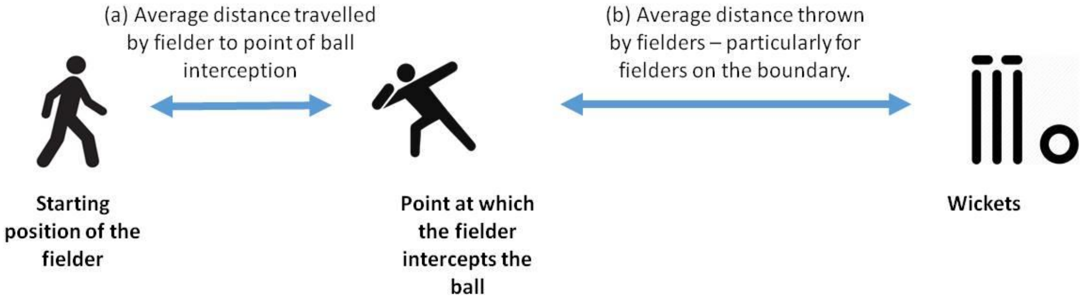

Figure III.VI: Motion analysis of overhead, side arm and submarine throwing

Participants were then asked to perform an additional six throws by running towards the series of beacons from a cone positioned five metres ahead of them, turn and throw overhead towards the stumps initially positioned behind the participant (Figure VIII.VI).

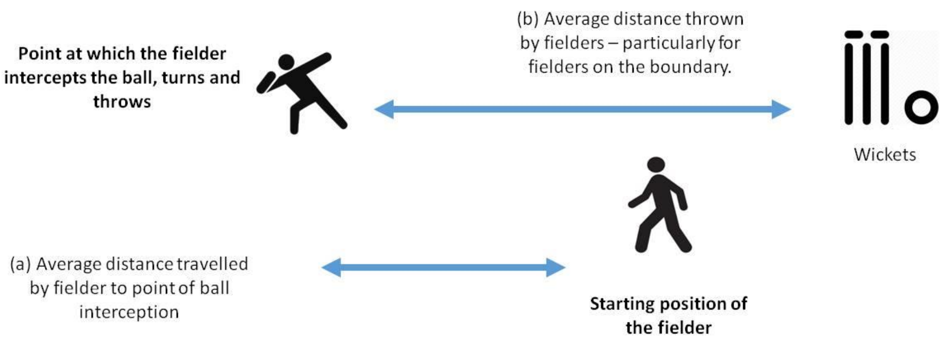

Figure III.V: Motion analysis of chasing a ball, turning and performing an overhead throw.

VI. MODELLING

VI.I Definition of Specific Joint Centres

The static calibration of subjects was performed with the subject standing in anatomical position. It was required to calculate and store the three dimensional (3D) locations of the static markers (Table VIII.II) relative to the associated segment technical co-ordinate system, in order to create virtual markers and joint centres during the motion analysis of throwing. As a result, the influence of skin artefact during dynamic movement was reduced.[201-204] These markers were removed after static calibration and prior to the commencement of the throwing trials.

a. Shoulder Joint Centre

The shoulder joint centre (SJC) is held relative to the technical co-ordinate systems of the acromion and upper arm clusters. The location of the SJC is expressed as a mean of the two positions relative to the acromion and upper arm technical co-ordinate systems in order to reduce the error locating the SJC during dynamic overhead movement.

Campbell et al (2009)[59] describe a regression equation to calculate the SJC based on the assumption that the humeral head is the centre of the shoulder. This equation is expressed as follows:

$$\mathbf{x = 96.2 - 0.302(CLAV - C7) - 0.364(height) + 0.385(mass)}$$

$$\mathbf{y = -66.32 + 0.30(CLAV - C7) - 0.432(mass)}$$

$$\mathbf{z = 66.48 - 0.531(AcrLR - C7) + 0.571(mass)}$$

Where:

CLAV = sternal notch (mm)

C7 = 7th cervical vertebrae (mm)

AcrLR = the midpoint of the lateral ridge of the acromial plateau (mm)

CP = the centre point between CLAV and C7 (mm)

Mass = Participant's mass (Kg)

Height = Participant's height (cm)

b. Elbow

The elbow joint centre (EJC) was defined as the midpoint between the markers placed on the medial (RELBM or LELBM) and lateral (RELBL or LELBL) epicondyles of the elbow during static calibration and were stored in the distal upper arm technical co-ordinate system.

c. Wrist

The wrist joint centre (WJC) was determined to be the midpoint between the markers placed on the radial (RWRR or LWRR) and ulnar (RWRU or LWRU) styloid processes during static calibration and was stored in the technical co-ordinate system of the forearm segment.

d. Hip

The hip joint centre (HpJCr) is held relative to the technical co-ordinate systems of the pelvis. The clinical gait model[180,205] utilises a regression equation to calculate the HpJCr, which is expressed as follows:

$$x = C \times \cos(\text{theta}) \times \sin(\text{beta}) - \cos(\text{beta})(\text{AsisTrocDist} + \text{mm})$$

$$y = -(C \times \sin(\text{theta}) - \text{aa})$$

$$z = -C \times \cos(\text{theta}) \times \cos(\text{beta}) - \sin(\text{beta})(\text{AsisTrocDist} + \text{mm})$$

Where:

C = 0.115(Mean Leg Length) – 15.3

*AsisTrocDist = 0.1288(Leg Length) – 48.56

aa = Half distance between LASI and RASI

mm = radius of the marker

theta = 0.5 radians

beta = 0.314 radians

*This is done independently for the left and right legs

e. Knee

The knee joint centre (KnJC) was determined to be the sum of half the knee breadth (distance between the markers placed on the medial (RKNM or LKNM) and lateral (RKN or LKN) femoral condyles) and the marker diameter. This provides the distance from the centre point of the marker to the joint centre and was stowed in either the RKN or LKN marker.

f. Ankle

Similarly, the ankle joint centre (AnkJC) was determined to be the sum of half the ankle breadth (distance between the markers placed on the medial (RANKM or LANKM) and lateral (RANK or LANK) malleolus) and the marker diameter. This provides the distance from the centre point of the marker to the joint centre and was stored in either the RANK or LANK marker.

IV.II Definition of Anatomical Co-ordinate Systems

An anatomical co-ordinate system is the reconstruction of each segment of the body as a rigid model during three dimensional motion analysis. It requires a minimum of three anatomical landmarks to represent bone motion.[59,178,205] Table VIII.IV summarises the anatomical co-ordinate systems with a description of the origin and axes of movement.

IV.III Definitions of Joint Co-ordinate Systems

The completion of the anatomical co-ordinate systems permits joint co-ordinate systems to describe the functional movement at each joint. All joint movement, with the exception of the shoulder, correspond to the standard Euler sequence as defined by Groot and Suntay (1983)[206] and is accepted as the International Society of Biomechanics' standard for defining joint co-ordinate systems.[59,178-180] The order of movement within the Euler sequence is flexion-extension, abduction-adduction and internal-external rotation; where the distal segment co-ordinate system moves about the proximal segment co-ordinate system. Thus, the joint rotation sequence is expressed as Z-X-Y (see Table VIII.VI and Figure VIII.VII).

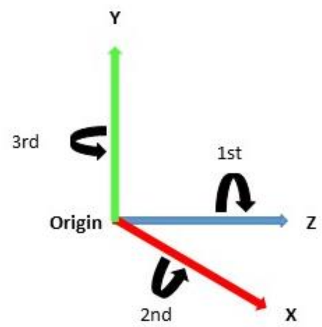

Figure III.VII: A schematic representation of Z-X-Y joint sequence of motion, where:

z-axis = flexion/extension, x-axis = abduction/adduction and y-axis = internal/external rotation.

Table III.IV: A summary of the anatomical co-ordinate systems used during the motion analysis of throwing.

Segment	Origin of Movement	Axis of Movement		
		Z (Vector points to right)	Y (Vector points cephalad)	X (Vector points anteriorly)
Head	Midpoint between LFHD and RFHD	LFHD to RFHD	Cross product of z-axis and the vector running from the midpoint of LFHD to RFHD to the origin	Cross product of z and y axis
Thorax	Midpoint of CLAV and C7 markers.	Cross product of y-axis and vector running from CLAV to C7	Vector running from midpoint of sternum and T10 markers to origin	Cross product of y and z.
Torso	Midpoint of STRN and T10 markers	Cross product of y-axis and vector running from STRN to T10	Vector running from the origin to the midpoint of the CLAV and C7 markers	Cross product of y and z.
Lumbar	L3	Cross product of y-axis and vector running from L3 to the midpoint between RUL and RLL markers	Vector running from the origin to the midpoint of STRN and T10 markers	Cross product of y and z.
Pelvis	Midpoint between RASI and LASI	Vector running from LASI to RASI	Cross product of z-axis and a vector running from a virtual sacral marker to the pelvis	Cross product of y and z.
Upper Arm	Elbow joint centre	Vector running from RELBM (medial) to RELB (lateral)	Vector running proximally from elbow joint centre to the shoulder joint centre (along the long axis of the humerus)	Cross product of y and z.
Forearm	Wrist joint centre	Vector running from RWRU (medial) to RWRR (lateral)	Vector running proximally from wrist joint centre to the elbow joint centre	Cross product of y and z
Hand	Midpoint of three hand markers (RHDR, RHDU and RHDC)	Vector running from RHDU (medial) to RHDR (lateral)	Vector running from the hand origin to the wrist joint centre	Cross product of y and z
Upper Leg	Midpoint between RKN and RKNM	Vector running from RKNM (medial femoral condyle) to RKN (lateral femoral condyle)	Vector running cephalad from the origin (along the long axis of the femur)	Cross product of y and z
Lower Leg	Midpoint between RANK and RANKM	Vector running from RANKM (medial malleolus) to RANK (lateral malleolus)	Cross product of x and z axis	Vector perpendicular to the torsional plane of tibia/fibula
Ankle	Midpoint between RANK and RANKM	Cross product of x and y	Vector running from the origin cranially, along the long axis of the tibia/fibula	Vector perpendicular to the frontal plane of the tibia/fibula.

Table III.V: Sequences and directions of rotations within the joint co-ordinate system, excluding the shoulder

Joint	Direction of Movement	Z	X	Y
Elbow	+	Flexion	Adduction (varus)	Pronation
	-	Extension	Abduction (Valgus)	supination
Hand	+	Flexion	Ulna deviation	N/A
	-	Extension	Radial deviation	N/A
Thoracolumbar	+	Flexion	Lateral flexion to left	Rotation to right
	-	Extension	Lateral flexion to right	Rotation to left
Lumbopelvic	+	Flexion	Lateral tilt to left	Rotation to right
	-	Extension	Lateral tilt to right	Rotation to left
Hip	+	Flexion	Adduction	Internal rotation
	-	Extension	Abduction	External rotation
Knee	+	Flexion	Adduction (varus)	Internal rotation
	-	Extension	Abduction (valgus)	External rotation
Ankle	+	Plantarflexion	Inversion	Pronation
	-	Dorsiflexion	Eversion	Supination

Table III.VI: Sequences and directions of rotations of the shoulder joint co-ordinate system

Joint	Direction of Movement	Y	X	Y
Shoulder	+	Rotation about the humerus to determine the plane of movement	Flexion	Internal rotation
	-		Extension	External rotation

However, the shoulder follows a Y-X-Y joint rotation sequence, as described in Table 4.7. This is due to the fact that shoulder movement is described as the humerus moving relative to the thorax.[59,178] The first "Y" is fixed to the thorax and corresponds to the thoracic co-ordinate system's y-axis. Movement about this axis defines the plane of humeral movement. Secondly, "X" is fixed to the humerus and parallels the upper arm co-ordinate system's x-axis (i.e.: abduction-adduction). Lastly, the second "Y" corresponds to the shaft of the humerus (elbow joint centre to shoulder joint centre) and represents shoulder rotation.

VII. DATA PROCESSING

The two dimensional data collected from each of the eight cameras was used to create three dimensional trajectories in Vicon Nexus (Oxford Metrics Ltd., Oxford, England), sampling at 500 Hz. Synchronised ground reaction force data were collected using two 900 x 600 mm force platforms (AMTI Inc., Watertown, MA, USA), sampling at 2000 Hz. Where trajectories were broken by less than 10 frames, a pattern copied from another marker on the same cluster, was used to fill it. Following residual analysis and visual inspection, data was filtered using a low-pass fourth-order Butterworth filter with cut-off frequency set at a mean square error of 6 and 100Hz, respectively. Raw markers were then modelled using the custom upper-body and lower body PlugInGait models (Version3.5)[184].

Three-dimensional joint angles and net resultant joint forces were calculated using a Newton-Eular inverse dynamics approach. All joint angles followed the Eular XYZ rotation sequence, except the shoulder which followed a YXY rotation sequence; and were described according to the joint co-ordinate systems recommended by the ISB.[178-180] Three-dimensional joint forces were expressed in newton (N). Shoulder force was determined as force applied by the trunk to the upper arm; whereas elbow force was calculated as force applied by the upper arm to the forearm.[4]

The overhead throw was analysed from neutral shoulder rotation to the reversal of shoulder rotation (internal to external rotation) following ball release and dominant arm deceleration. Specific phases of the throwing cycle are described as follows:

i. Preparatory phase: From neutral shoulder rotation to the point of maximum shoulder external rotation (MER)
ii. Arm acceleration: From MER to the point of ball release (BR)
iii. Ball release (BR): Point at which the ball is released from the dominant hand, directed towards the target
iv. Arm deceleration: From BR to maximum shoulder internal rotation (MIR), prior to the reversal of shoulder rotation

Data for each participant's dominant throwing limb were averaged over three successful good-quality trials. Joints of interest included shoulder, elbow, thoraco-lumbar, lumbo-pelvic and hip joint angles. Kinematic and kinetic data are represented as wave-forms that changed continuously throughout the overhead throw and were defined with 101 data points, one for each percentage of the overhead throw.

VIII. ANTHROPOMETRIC MEASUREMENTS

Anthropometric data included the measurement of height and mass. In addition bilateral measurements of leg length, the breadths of the ankle, knee, elbow and third metacarpophalangeal joints were taken. All measurements adhered to the procedures recommended by the International Society for Advancement of Kinanthropometry.[207]

a. Height and Mass

Height was measured in standing using a flexible plastic tape (Zhecheng Lida Essential Co., Ltd. 2012 Butterfly brand soft tailor tape), calibrated in centimetres (cm) with millimetre (mm) graduations. Subjects were required to stand tall with both heels and the posterior aspect of their head flush against a wall. Height measurement was noted on inhalation and recorded in mm.

Mass was measured using a calibrated digital scale (Zhongshan YESHM Commodities Co., Ltd. 1999, Ultra-portable personal scale) and recorded in kilograms (kgs), rounded off to the nearest 0.1 kg.

b. Leg Length

Leg length was measured with the participant standing in anatomical position, using a flexible plastic tape (Zhecheng Lida Essential Co., Ltd. 2012 Butterfly brand soft tailor tape). The distance from the ipsilateral ASIS to the medial malleolus was noted for the left and right legs respectively.

c. Breadths

The four breadths were measured with the participants standing in a relaxed position, using a large sliding anthropometer (Lafayette Instrument Company, 1947 Model 01291). Both the dominant and non-dominant side were measured.

i. Ankle

The ankle breadth was measured as the distance between the medial and lateral malleoli.

ii. Knee

The knee breadth was measured as the distance between the medial and lateral femoral condyles. The knee is unlocked during this measurement allowing for ease of palpation of the bony eminences.

iii. Elbow

Participants are positioned in standing with 90° shoulder flexion and full elbow flexion so that the hand is placed palm down on the ipsilateral shoulder of the arm being measured. The elbow breadth was measured as the distance between the medial and lateral humeral epicondyles.

iv. Third Metacarpal Phalangeal Joint

Participants stand with arms by side and elbows flexed to 90° with full forearm supination and the hand extended with fingers straight. The breadth of the third MCPJ was measured as the distance between the dorsal and volar aspects of the head of the third metacarpal.

APPENDIX IV: INFORMED CONSENT FORM – CHAPTERS 5 TO 7

PARTICIPANT INFORMATION SHEET

Motion analysis of three throwing techniques utilised by elite level cricketers

Dear Participant

I am a doctoral candidate with the Department of Human Biology, University of Cape Town. I will be conducting a study to analyse the motion used by cricketers when performing an underarm or submarine, sidearm and overhead throw.

All information obtained within this study will be used to assist me with the requirements for my thesis for the PhD Exercise Science and Sport Medicine degree. This study has been granted Ethical Approval by the Human Research Ethics Committee, Faculty of Health Sciences, University of Cape Town (REC REF).

Please take your time to read this form thoroughly, before signing.

Prior to your inclusion within this study, you will be expected to complete and sign this form and complete a personal questionnaire.

Why is this study being done?

A number of studies have been conducted on throwing technique, however the vast majority of these studies have analysed throwing and pitching in baseball. In addition, these studies have largely neglected the movement of the shoulder blade when performing a throw. The study will determine the movement of the entire upper quadrant (upper back, shoulder blade, shoulder, arm and hand) and pelvis when performing the three throwing techniques commonly used by cricketers. Further, the results of this study will serve as a platform to determine the potential risk for shoulder injury when performing the throwing action and will aid in the identification of the most optimal and efficient throw.

Why am I being asked to take part in this study?

You are being asked to participate in this study as you are an elite cricketer, familiar with the action of throwing and the various techniques utilised to throw while fielding. In addition, you have returned to a minimum of one fielding and two cricket specific (net) sessions per week, for a minimum period of three weeks. Therefore you are adequately conditioned for throwing analysis.

How many people will take part in the study?

Twenty five cricketers from the Western Province Franchise and Amateur Squads will be participating in this study.

How long will the study last?

This study forms part of a broader investigation which will last for approximately one and a half years. Data for this study will be collected over a period of two to three months, where after it will be analysed and finally collated with the data from the broader investigation. Your participation will be required for a single once-off testing session.

What do we do to decide if you are eligible to take part in the study?

You are eligible to participate in this study if you fulfil the following criteria:

- 18 years of age or older
- Perform at least two cricket specific (net) and one fielding training sessions per week (for a minimum of three weeks),
- Have a healthy shoulder with no pain
- Have never had previous shoulder surgery or a traumatic shoulder injury,
- Do not experience any neck stiffness
- Have no pins and needles, tingling or burning sensations down one or both of your arms

What will happen if you decide to take part in the study?

You will be asked to attend one session of approximately an hour duration, at the Biomechanics Laboratory, Sport Science Institute of South Africa. During this session, you will be required to complete six throws of each throwing technique (underarm, sidearm, overhead) in the order specified by drawing a card labelled A, B or C from a hat.

You will be asked to complete a questionnaire regarding your shoulder function related to activities of daily living and sport. A physical assessment including your height, weight and anthropometric tests will be conducted. You will be familiarized with the testing procedure utilised within this study, by way of explanation. Any questions and/or concerns will be answered and addressed appropriately.

The testing protocol to be utilised during this study, is described below. Please note that for the motion analysis, you will be required to wear shorts.

1. Anthropometric Data

a. Body Mass

Your body mass will be recorded by you standing barefoot in your shorts, on a scale.

b. Height

Your height will be measured by you standing barefoot in your shorts, with your heels flush against a wall. A ruler will be placed on top of your head and a line drawn to mark your height.

c. Anthropometric Tests

These tests are done in order to assess your body fat percentage. Seven skin fold measurements will be taken with a calliper, which gently pinches the skin, lifting it away from your muscle at your bicep, triceps, upper back, just below the shoulder blade, above your hip, on your calf, thigh and abdomen.

2. Placement of Anatomical Markers

A total of 39 reflective markers will be secured to your body using fixomull, a hypoallergenic tape. These markers will be placed on a variety of bony landmarks of your pelvis, upper back, collar bone, shoulder blade, upper arm, elbow, forearm and hand.

3. Warm-up

You will be required to complete a standard 10 minute warm-up with the marker set attached, prior to the assessment of throwing technique. This will include a series of dynamic stretches to the lower back, upper and lower limbs, followed by a progressive throwing sequence. The warm-up protocol will reduce your risk for injury and familiarize you to throwing with the full set of reflective markers.

4. Motion Analysis of Throwing

You will be required to complete six throws of each of the underarm or submarine, sidearm and overhead throws, in the sequence indicated on card A,B or C drawn from a hat. For each throw, you will be required to run in towards a cone placed five metres away from you; collect a ball from the top of a beacon and throw towards a set of stumps. You may walk back to the start. Once you have completed six throws of the specified technique, a two minute rest period will occur. This process will be repeated until all three techniques have been analysed.

The motion analysis of all three throwing techniques will take approximately 15 minutes to complete. Upon completion of the motion analysis you will be asked to rank the three techniques in order of preference.

What are the risks and discomforts of the study?

There is minimal to no risk associated with this study.

A possible, temporary development of post-exercise soreness or stiffness to the back and shoulder specifically. This soreness or stiffness is a normal occurrence after performing exercise you have not done in a while, and will usually disappear within three to four days. As the testing protocol is less intense than a fielding practice or match situation this is unlikely to occur.

Are there any benefits to you for taking part in the study?

You will receive your body composition and anthropometric measurements, as well as a summary of the results of the study. You will also obtain a greater understanding of the throwing technique and potentially reduce your risk of shoulder pain and/or injury by choosing a technique that is most beneficial to you.

What happens if I choose not to participate in the study?

Your participation within this study is completely voluntary and you have the right to withdraw from this study at any time, without providing reasons. Further, your decision not to participate within this study will be kept confidential; will remain undisclosed to your coach and/or management staff; and will not compromise your selection for representation in the respective Western Province franchise and/or amateur cricket teams.

What will happen when the study is over?

At the conclusion of the study, data collected will be published in respective medical journals and made available to you, as well as your respective coach and/or other management staff. Raw data will be kept in a locked filing cabinet for a period of five years, where after all information will be shredded.

Who will see the information which is collected about you during the study?

All information recorded will be held private and confidential. This will be achieved by utilizing a coding system, whereby each participant’s codes and personal information will be held in a locked filing cabinet, by an independent auditor for the duration of the study.

Further, participants will not be identified in any publication associated with this study. Lastly, only the principal investigator and her supervisors will have access to your information during this study.

Who do I speak to (or contact) if I have questions about the study?

If at any time you have any questions or concerns about this study, please feel free to contact any of the individuals listed below. Please be assured that all enquiries will remain private and confidential

Student Investigator: Megan Dutton

Physical Address: Division of Exercise Science and Sports Medicine,
Department of Human Biology
University of Cape Town
Sports Science Institute of South Africa
Boundary Road
Newlands
7700

Tel number: 076 302 4390 or 082 787 5753

E-mail: megandutton@gmail.com

Principal Investigator: Janine Gray

Physical Address: Division of Exercise Science and Sports Medicine,
Department of Human Biology
University of Cape Town
Sports Science Institute of South Africa
Boundary Road
Newlands
7700

Tel number: (021) 650 4557

Fax number: (021) 650 1796

E-mail: janineg@cricket.co.za

Professor Marc Blockman

Chairperson, Faculty of Health Sciences Research Ethics Committee

Physical address:	E52 – 23 Old Main Building
	Groote Schuur Hospital
	Observatory
	7925
Tel number:	(021) 406 6492
Fax number:	(021) 406 6411

The UCT's Faculty of Health Sciences Human Research Ethics Committee can be contacted on 021 406 6338 in case you have any ethical concerns or questions about your rights or welfare as a participant on this research study.

Please note that UCT does offer a no-fault insurance that will cover all participants in the event that something may go wrong. This insurance will provide prompt payment of compensation for any trial-related injury according to the Association of the British Pharmaceutical industry (ABPI) guidelines (1991). These guidelines recommend that UCT, without any legal commitment, should compensate you without you having to prove that UCT is at fault. An injury is considered trial-related if, and to the extent that, it is caused by study activities. You must notify the study investigators immediately of any injuries during the trial, whether they are research-related or other related complications. UCT reserves the right not to provide compensation if, and to the extent that, your injury came about because you chose not to follow the instructions that you were given while taking part in the study. Your right in law to claim compensation for injury where you prove negligence is not affected.

PARTICIPANT CONSENT FORM

Motion analysis of three throwing techniques utilised by cricketers

I, the undersigned, have been fully informed about the study entitled: **"Motion analysis of three throwing techniques utilised by cricketers"** to be conducted by researchers from the UCT/MRC Research Unit for Exercise Science and Sports Medicine within the Department of Human Biology, Faculty of Health Sciences, University of Cape Town.

Please tick the parts of this study that you consent to participating in:

☐ I consent to participating in the motion analysis of three throwing techniques to be performed by a UCT research investigator. I am aware that I will be required to perform a warm-up and 18 throws (6 per technique). The testing will be conducted at the Sports Science Institute of South Africa and will require approximately 60 minutes of my time.

The protocol for this study has been described in the Participant Information document and I have had an opportunity to ask any questions about the procedures and results of the tests.

I have been fully informed about the risks inherent in participation in this trial. I understand that all information collected during this study will be treated confidentially, will only be used for scientific research purposes and that my name and personal particulars will not be released under any circumstances. I am aware that although there is no direct personal benefit to me, the study findings may benefit me in the long term.

I have been informed that I am able to withdraw from the study at any time if I so wish, without providing an explanation. I understand that I will receive, where applicable, feedback pertaining to the results of the performance variables for throwing.

I agree to participate in the study.

_______________________	_______________________	_________
Signature of Volunteer	Full Name (please print)	Date

_______________________		_________
Signature of Investigator	Megan Dutton	Date

APPENDIX V: DEMOGRAPHIC DATA AND ANTHROPOMETRIC COLLECTION FORM

SUBJECT CODE: ***DATE:***

1. Personal Data

Please complete the table below:

Name					
Surname					
Date of Birth					
Age					
Team					
Handedness	**Left**			**Right**	
Position	**Bowler**	**Batsmen**		**All Rounder**	**Wicket keeper**
If bowler	**Fast**	**Medium**	**Slow**	**Wrist Spinner**	**Finger spinner**

2. Contact Details

Please complete the table below:

Contact Number	
E-mail Address	

3. General Health Status

Do you suffer from any of the following? If yes, please specify frequency (i.e.: twice a week) and medication you make use of, if applicable.

Condition	Yes	No	Frequency	Medication Used
Asthma				
Diabetes				
Hypertension				
Epilepsy				
Dizziness				
Nausea				
Migraines				
Pins and needles in both arms at the same time				
Glove like pins and needles or excessively sweaty palms				

4. Cricket Specific Data

4.1 Please indicate where you prefer to field.

Slip	Inner Ring	Boundary

4.2 What is your preferred throwing style?

Underarm/Submarine Flick	Side Arm	Overhead

4.3 Please indicate your frequency of training per **week**, by marking an 'X' in the appropriate box.

Hours	0–30min	30min–1 hr	1–2 hrs	2–3 hrs	3-4 hrs	4-5 hrs	5-6 hrs	6-7 hrs	> 7hrs
Nets – Batting									
Nets - Bowling									
Fielding									
Fitness									
Strength Training									

5. Injury History

Please indicate whether you have sustained any of the following injuries, by marking an 'X' in the yes/no column. If yes, please complete the entire row of questions.

Injury	Yes	No	Side (where applicable)		Date of injury	Is the injury still present?	
			Left	Right		Yes	No
Whiplash							
Headache							
Neck Injury							
Shoulder muscle tear							
Thrower's Shoulder/Impingement							
Upper arm muscle tear							
Pain down either or both arms							
"Tennis Elbow"							
Upper back pain							
Lower back pain							

APPENDIX VI: ETHICAL APPROVAL FOR ALL STUDIES CONDUCTED IN THIS THESIS

UNIVERSITY OF CAPE TOWN
Faculty of Health Sciences
Human Research Ethics Committee

Room E52-24 Old Main Building
Groote Schuur Hospital
Observatory 7925
Telephone [021] 404 7682 • **Facsimile** [021] 406 6411
Email: nosi.tsama@uct.ac.za
Website: www.health.uct.ac.za/fhs/research/humanethics/forms

08 July 2016

HREC REF: 364/2016

Dr J Gray
Human Biology
Exercise Science & Sports Medicine
Sports Science Institute

Dear Dr Gray

PROJECT TITLE: THE CRICKETING SHOULDER: BIOMECHANICS AND ANALYSIS OF POTENTIAL INJURY RISK FACTORS TO THE SHOULDER IN ELITE CRICKETERS (PhD candidate- Megan Dutton)

Thank you for submitting your response letter to the Faculty of Health Sciences Human Research Ethics Committee dated 04 July 2016.

It is a pleasure to inform you that the HREC has **formally approved** the above-mentioned study.

Approval is granted for one year until the 30th July 2017.

Please submit a progress form, using the standardised Annual Report Form if the study continues beyond the approval period. Please submit a Standard Closure form if the study is completed within the approval period.
(Forms can be found on our website: www.health.uct.ac.za/fhs/research/humanethics/forms)

We acknowledge that the student Megan Dutton will also be involved in this study.

Please note that for all studies approved by the HREC, the principal investigator **must** obtain appropriate institutional approval before the research may occur.

Please quote the HREC REF in all your correspondence.

Please note that the ongoing ethical conduct of the study remains the responsibility of the principal investigator.

Yours sincerely

pp T.Burgess

PROFESSOR M BLOCKMAN
CHAIRPERSON, FHS HUMAN RESEARCH ETHICS COMMITTEE
Federal Wide Assurance Number: FWA00001637.
Institutional Review Board (IRB) number: IRB00001938

HREC 364/2016

APPENDIX VII: INFORMED CONSENT FORM – CHAPTERS 3 AND 4

PARTICIPANT INFORMATION SHEET

A study to identify the risk factors contributing to the development of non-specific shoulder pain and injury in cricketers.

Dear Participant

I am a doctoral candidate with the Department of Human Biology, University of Cape Town. I will be conducting a study to identify the potential risk factors associated with the development of non-specific shoulder pain and injury in cricketers.

All information obtained within this study will be used to assist me with the requirements for my thesis for the PhD Exercise Science and Sport Medicine degree. This study has been granted Ethical Approval by the Human Research Ethics Committee, Faculty of Health Sciences, University of Cape Town (HREC: 364/2016).

Please take your time to read this form thoroughly, before signing.

Prior to your inclusion within this study, you will be expected to complete and sign this form and complete a personal questionnaire.

Why is this study being done?

Currently the incidence of shoulder injury in cricket is underestimated as previous studies have failed to include cricketers who have been able to play despite injury. In addition, all cricketers are required to throw, irrespective of specialty. Within baseball, repetitive throwing is thought to result in some soft tissue and bony adaptation within the shoulder joint complex. Whether or not, these adaptations are beneficial to performance or pathological remains unknown. The study will determine the potential risk factors associated with the development of non-specific shoulder pain and injury, by performing a battery of pre-season shoulder screening tests and monitoring cricketers over a season for the development of shoulder pain and injury. Further, the results of this study will serve as a platform upon which to address the question of whether or not anatomical adaptations to throwing are adaptive or pathological. In addition, the potential causative factors for pain and injury can be identified. Lastly, an overhead sports shoulder specific treatment and rehabilitation protocol can be developed.

Why am I being asked to take part in this study?

You are being asked to participate in this study as you are a part of the squad for your cricket franchise for the 2016/2017 season. In addition, as you are an elite cricketer performing at a high level of competition regularly, your risk for potential injury is higher than that of a social athlete.

How many people will take part in this study?

All cricketers who are a part of the respective Cricket South Africa franchise squads for the 2016/2017 season will be asked to participate in this study

How long will the study last?

This study forms part of a broader investigation which will last for approximately one and a half years. Data for this study will be collected over a period of one cricket season (2016/2017 season), where after it will be analysed and finally collated with the data from the broader investigation. Your participation will include a single pre-season testing session. Your injury data will then be collected by your respective franchise physiotherapist and/or doctor throughout the season.

What do we do to decide if you are eligible to take part in the study?

You are eligible to participate in this study if you fulfil the following criteria:

- 18 years of age or older,
- Form part of the respective Cricket South Africa franchise cricket squads for the 2016/2017 season,
- Perform at least two cricket specific (net) and one fielding training sessions per week,
- Participate in a minimum of one format (Four day, One Day or T20) cricket matches throughout the 2016/2017 season

What will happen if you decide to take part in the study?

You will be asked whether or not you would like to participate in a Shoulder Screening of approximately 30 minutes duration, prior to your pre-season screening protocol at your respective cricket franchise physiotherapist's office. Participation is voluntary. Your decision on participation will remain confidential; will not be disclosed to your respective coaching and/or management staff; and will not compromise your selection for your franchise cricket team in any way or form.

You will be asked to complete a questionnaire regarding your shoulder function related to activities of daily living and sport. A physical assessment including your height, weight and anthropometric tests will be conducted. You will be familiarized with the testing procedure utilised within this study, by way of explanation. Any questions and/or concerns will be answered and addressed appropriately.

The testing protocol to be utilised during this study, is described below. Please note that for the shoulder specific screening, you will be required to wear shorts.

1. Kerlan-Jobe Orthopaedic Clinic Shoulder and Elbow Score

This is a one page questionnaire which is divided into three sections, relating to function and athletic performance (four questions), symptoms related to the upper limb (five questions) and interpersonal relationships related to performance (one question). Each question is measured using a scale where the extreme left indicates lowest level of function or performance and greatest severity of the symptoms assessed, and the extreme right the highest level of function or performance and lowest severity of symptoms assessed. It will take you approximately five minutes to complete the questionnaire.

2. Anthropometric Data

a. Body Mass

Your body mass will be recorded by you standing barefoot in your shorts, on a scale.

b. Height

Your height will be measured by you standing barefoot in your shorts, with your heels flush against a wall. A ruler will be placed on top of your head and a line drawn to mark your height.

c. Anthropometric Tests

The results of these tests will be requested from your franchise trainer/biokineticist. These tests are done in order to assess your body fat percentage. Seven skin fold measurements will be taken with a calliper, which gently pinches the skin, lifting it away from your muscle at your bicep, triceps, upper back, just below the shoulder blade, above your hip, on your calf, thigh and abdomen.

3. Shoulder Specific Tests

The following clinical tests will be performed on your shoulder (in a variety of positions such as standing, sitting or lying on your back):

a. Pain Provocation Tests (used to assess the presence of shoulder pain by a yes/no answer):

i. Hawkin's-Kennedy Test

ii. Jobe's Test

b. Measurement of your passive range of shoulder joint rotation

c. Measurement of upward scapula rotation range of motion

d. Isometric muscle strength of your shoulder rotator muscles

i. Internal (inward) rotators

ii. External (outward) rotators

e. Isometric muscle strength of shoulder blade stabilisers

i. Serratus anterior muscle

ii. Upper Trapezius muscle

iii. Lower trapezius muscle

f. Muscle length of your pectoralis minor muscle (deep chest muscle)

g. Flexibility of your posterior shoulder complex (back of your shoulder)

4. Ultrasonographic Measurement of the Shoulder

The following ultrasonographic measurements will be performed with you sitting in a chair with your arm placed in a relaxed position on either your lap or your hip:

a. Measurement of the distance between your acromion (a bony process from your shoulder blade) to the head of your humerus (upper arm bone)

b. Measurement of the thickness of your supraspinatus tendon (one of the rotator cuff tendons).

5. Hip Specific Tests

The following clinical tests will be performed on your hips (in a variety of positions such as sitting with legs over the side of the bed or lying on your back):

a. Measurement of your passive hip rotation range of motion

b. Isometric muscle strength of you hip abductor (side-side stabilizer) muscle

Injury Surveillance

Your injuries sustained during the 2016/2017 cricket season will be tracked and monitored via the Peformax database as well as via correspondence with your respective franchise physiotherapists.

What are the risks and discomforts of the study?

The associated risks with participation within this study include:

- A possible, temporary increase in current shoulder pain experienced, during the screening, as some of the testing protocols utilised may cause shoulder pain. However, every effort will be made to minimise the extent of pain during testing. All tests used are accepted clinical tests used to assess pain in a joint, and strength and length of shoulder muscles. Testing will be discontinued if any sustained increase in your shoulder pain occurs during any of the testing procedures.
- The development of post-exercise soreness or stiffness to the back and shoulder specifically. This soreness or stiffness is a normal occurrence after performing exercise you have not done in a while, and will usually disappear within three to four days.

Are there any benefits to you taking part in the study?

You will receive your body composition and anthropometric measurements, as well as a summary of the results of the study. You will also obtain a greater understanding of your current shoulder "health" and risk for potential shoulder pain and/or injury.

What happens if I choose not to participate in the study?

Your participation within this study is completely voluntary and you have the right to withdraw from this study at any time, without providing reasons. Further, your decision not to participate within this study will be kept confidential; will remain undisclosed to your respective franchise coach and/or management staff; and will not compromise your selection for representation in the respective franchise cricket teams.

What will happen when the study is over?

At the conclusion of the study, data collected will be published in respective medical journals and made available to you, as well as your respective coach and/or other management staff. Raw data will be kept in a locked filing cabinet for a period of five years, where after all information will be shredded.

Who will see the information which is collected about you during the study?

All information recorded will be held private and confidential. This will be achieved by utilizing a coding system, whereby each participant's codes and personal information will be held in a locked filing cabinet, by an independent auditor for the duration of the study. Further, participants will not be identified in any publication associated with this study. Lastly, only the principal investigator and her supervisors will have access to your information during this study.

Who do I speak to (or contact) if I have questions about the study?

If at any time you have any questions or concerns about this study, please feel free to contact any of the individuals listed below. Please be assured that all enquiries will remain private and confidential.

Student Investigator: Megan Dutton

Physical Address: Division of Exercise Science and Sports Medicine

Department of Human Biology

University of Cape Town

Sports Science Institute of South Africa

Boundary Road

Newlands

7700

Tel number: 076 302 4390 or 082 787 5753

E-mail: megandutton@gmail.com

Principal Investigator: Supervisor: Janine Gray

Physical Address: Division of Exercise Science and Sports Medicine

Department of Human Biology

University of Cape Town

Sports Science Institute of South Africa

Boundary Road

Newlands

7700

Tel number: (021) 650 4557

Fax number: (021) 650 1796

E-mail: janineg@cricket.co.za

Professor Marc Blockman

Chairperson, Faculty of Health Sciences Research Ethics Committee

Physical address: E52 – 23 Old Main Building

Groote Schuur Hospital

Observatory

7925

Tel number: (021) 406 6492

Fax number: (021) 406 6411

The UCT's Faculty of Health Sciences Human Research Ethics Committee can be contacted on 021 406 6338 in case you have any ethical concerns or questions about your rights or welfare as a participant on this research study.

Please note that UCT does offer a no-fault insurance that will cover all participants in the event that something may go wrong. This insurance will provide prompt payment of compensation for any trial-related injury according to the Association of the British Pharmaceutical industry (ABPI) guidelines (1991). These guidelines recommend that UCT, without any legal commitment, should compensate you without you having to prove that UCT is at fault.

An injury is considered trial-related if, and to the extent that, it is caused by study activities. You must notify the study investigators immediately of any injuries during the trial, whether they are research-related or other related complications. UCT reserves the right not to provide compensation if, and to the extent that, your injury came about because you chose not to follow the instructions that you were given while taking part in the study. Your right in law to claim compensation for injury where you prove negligence is not affected.

PARTICIPANT CONSENT FORM

A study to identify the risk factors contributing to the development of non-specific shoulder pain and injury in cricketers.

I, the undersigned, have been fully informed about the study entitled: **"A study to identify the risk factors contributing to the development of non-specific shoulder pain and injury in cricketers"** to be conducted by researchers from the UCT/MRC Research Unit for Exercise Science and Sports Medicine within the Department of Human Biology, Faculty of Health Sciences, University of Cape Town.

Please tick the parts of this study that you consent to participating in:

☐ I consent to my shoulder musculoskeletal screening data being released to the principle investigator for part of the analysis as detailed above. I also agree to allow my respective franchise physiotherapist to complete an injury recall questionnaire on my behalf at the end of the season.

☐ I consent to participating in the shoulder musculoskeletal screening to be performed by a UCT research investigator. I am aware that I will be required to perform a variety of tests, as detailed above. The testing will be conducted at my franchise training ground and will require approximately 30 minutes of my time.

The protocol for this study has been described in the Participant Information document and I have had an opportunity to ask any questions about the procedures and results of the tests.

I have been fully informed about the risks inherent in participation in this trial. I understand that all information collected during this study will be treated confidentially, will only be used for scientific research purposes and that my name and personal particulars will not be released under any circumstances. I am aware that although there is no direct personal benefit to me, the study findings may benefit me in the long term.

I have been informed that I am able to withdraw from the study at any time if I so wish, without providing an explanation. I understand that I will receive, where applicable, feedback pertaining to the results of the performance variables for throwing.

I agree to participate in the study.

______________________	______________________	________
Signature of Volunteer	Full Name (please print)	Date
______________________		________
Signature of Investigator	Megan Dutton	Date

APPENDIX VIII: INJURY DATA SPREADSHEET

Player		Example
Sustained a shoulder injury?	*Yes*	x
	No	
If "Yes", please complete below:		
Shoulder Injured	*Dominant*	x
	Non-Dominant	
Clinical Diagnosis	*Shoulder Impingement*	
	Rotator Cuff Tendinopathy	x
	Shoulder Instability	
	Muscle Strain	
	Labral Injury	
	Other, please specify:	
Nature of injury	*1st Incident*	
	Chronic	
	Recurrent	x
	If recurrent, season of previous incident	2014
How did the injury occur?	*Acute*	
	Gradual	x
When did it occur?	*Practice*	x
	Match	
	Other, please specify	
During which activity did it occur?	*Bowling*	
	Batting	
	Fielding - Throwing	x
	Fielding - Catching	
	Fielding - Diving	
	Other, please specify	
If injury occurred during match, please indicate type	*Domestic T20*	
	Domestic One Day	
	Domestic 4 Day	
	International T20	
	ODI	
	International Test	
	Not Applicable	x
Did the shoulder injury affect the player's ability to bat, bowl and field?	*Yes*	x
	No	
Did the player adapt their throwing technique in response to the injury?	*Yes*	x
	No	
Did the player field in a specific area due to the shoulder injury?	*Yes*	x
	No	
Did the injury affect the player's selection?	*Yes*	
	No	x