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The technical assessment of individual performance in rugby union players

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The technical assessment of individual performance in rugby union players.

Andrew Craig Green

A thesis submitted to the Faculty of Health Science, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree Doctor of Philosophy.

Johannesburg, 2016

Declaration

I, Andrew Green, declare that the work contained in this thesis is my own work, except to the extent indicated in the acknowledgements section.

This thesis is being submitted for the degree of Doctor of Philosophy, at the University of the Witwatersrand, Johannesburg, South Africa.

This work has not been submitted for any other degree or examination in this or any other university.

_____ 16 July 2016

(signature of candidate)

Abstract

Performance in Rugby Union relies on a wide variety of contributions of different individual skills. Individual tasks, such as passing, kicking or scrummaging are dependent on an individual's ability and may vary according to a player's playing position. The focus of this thesis is a series of studies which have assessed the performance of individual rugby players (particularly related to the assessment of passing, kicking and scrummaging) and to evaluate such performance in relation to factors (most often kinematic factors) which have been identified and correlated to better performance. The main body of this thesis includes seven studies, in the form of original papers, which firstly describe the factors which contribute to rugby passing accuracy (two studies), thereafter two studies which focus on kicking success are described. The final three studies describe the development of a new device for measuring individual scrummaging performance. These studies also investigated: the role of body positioning in the generation of scrummaging force; and assessed how such factors may respond to the fatigue experienced over the duration of a rugby game.

One skill that all rugby players require is the ability to effectively pass the ball to another player. Two original research studies are presented in this thesis that describe multiple approaches to accomplishing passes in rugby players. A target frame was constructed, and the ball position relative to the centre of the target frame was recorded and reported as the accuracy error distance. The first study of this thesis assessed the accuracy of the running pass using self-selected passing strategies. Two strategies were identified: in-step passing and out-of-step passing, although differences in the step sequence resulted in no change in the pass accuracy. The second study evaluated the differences in accuracy and kinematic strategies used to execute the ground pass. Passes performed using a side-on body orientation were more accurate than those performed using a front-on body orientation. The two body orientations utilised different kinematic strategies: front-on relied on torso and pelvic

rotations, whereas the side-on relied less on trunk rotations and utilised greater extension angles of the stance arm.

Match victory can also be determined by individual kicking success, but in this case is reliant on the role of individual kickers in a team. In the third study, kinematic predictors of place kicking accuracy and distance were explored. Larger axial torso and pelvic rotations were related to further place kicks, and greater extensions of the stance arm was related to more accurate place kicks. However larger torso rotations, which were positively related to kicking distance, were negatively related to kick accuracy. The fourth study was devised to compare the kinematic sequences of two points scoring kicking types. The comparisons suggest that the body kinematics used during the place and drop kicks were not different, although kicking distances were further in the place kick.

The fifth study of this thesis evaluated the feasibility of a custom individual scrummaging ergometer. The design, calibration, and measurement accuracy of the individual scrum ergometer are presented. Application of the ergometer revealed differences in individual scrummaging attributes, such as position of force application and centre of pressure variation, of players in different playing positions. No differences were observed in the force magnitude between playing positions.

The sixth study investigated individual kinematic scrum performance using conventional kinematic techniques and the custom individual scrum ergometer. The results highlight the role of a lower body height and wider stance in the attainment of greater individual scrummaging forces. No static kinematic variables were related to individual scrum performance. The final study investigated the effects of fatigue resulting from a simulated rugby match on individual scrummaging kinetics and kinematics. Although an increase in psychological and physiological markers of fatigue were observed, no scrummaging

differences were noted in peak forces or in body kinematics at peak force following the rugby match simulation.

In conclusion, the identification of performance related factors and the invalidation of others which have been identified in this body of work, may provide an opportunity for performance tailoring strategies of individual players, selection strategies for teams or even the tailoring of training practices to optimise performance. As an initial set of studies, however, many of these factors still need reassessment and validation by subsequent research and therefore this work has provided a number of research possibilities for later studies. To this end, a suggested topic of ensuing research may be to assess the repeatability of predictive power of the variables identified here, whether they are uniformly predictive over time or in different subject groups and lastly whether the individual performances (which were the focus of these studies) are translatable into team performance.

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Preface and Description of Thesis Sections

Rugby is currently played by over one hundred national sides worldwide. A derivation of the game, rugby sevens will once again be contested at the Olympic Games in the year of submission of this thesis (2016). The first game of 'rugby football' is said to have been played at a Warwickshire public school with which it shares its name.

The current thesis focuses on the game of Rugby Union, which hereafter will simply be referred to as rugby. It should be noted that other forms of rugby are popularly played around the world including rugby league, rugby sevens, touch rugby, beach rugby, underwater rugby and wheelchair rugby. Much of the research here however (particularly related to passing and kicking) are also relevant to these other codes.

The study of sports performance in general and rugby performance in particular has been conducted using various methods and the application of such research has been to the improvement of performance, the understanding of the causes of injury and the scientific understanding of the dynamics of the factors which drive athletic performance. In contrast to many sports, the study of performance in rugby is more difficult to quantify as a team's performance is largely dependent on different contributions of individuals to that team's chances of success and is also only directly measureable relative to the performance of an opposing team. Although such measures of performance (identification of a winning team or the recording of score differences achieved during rugby games) are useful as direct measures of a rugby team's performance, this data offers little insight into the component performances of the individuals whose efforts are combined in a winning effort. To address this issue, the current thesis takes the approach of assessing the individual aspects of performance in an attempt to elucidate some of the fundamental contributors to the performance of individuals in a rugby game. The sections that follow describe how this body of work intends to

contribute to a better understanding of the technical assessment of individual contributions of rugby players towards a collective team performance.

Chapter 1 provides a brief account of the historical context of rugby and a description of the current game including the features of rugby game play. The literature review continues by examining the assessment of field-based team sports performance and then specifically focuses on research conducted on the performance of rugby tasks and the identification of performance outcomes. Finally, a review of the current knowledge of the effects of fatigue on sports performance is described. The rationale and objectives for the current studies, which originates from the described literature, follows.

In the chapters following the introductory chapter, the series of studies, presented as papers, which make up the main body of this thesis are described. These seven studies are mainly concerned with the quantification and analysis of performance of three rugby specific tasks, namely: passing, kicking, and scrummaging.

The first and second studies (Chapter 2 and 3) are related to a skill that all players in a rugby team require: the ability to pass. Passing in rugby is performed while running, or from the largely static position behind the breaks in phases. The first of these (Chapter 2) describes the kinematic factors associated with the running pass with respect to passing accuracy. This is followed by a second study (Chapter 3) describing the kinematics and accuracy of the comparably static ground pass.

The third and fourth studies (Chapter 4 and 5) focus on the kinematic performance related to the place and drop kicks. Chapter 4 assesses the kicking techniques of rugby place-kicking in an attempt to understand factors that may optimise kicking performance. Chapter 5 assesses the potentially different technical approaches to performing the place- and drop-kicks.

Following this, perhaps the most positional specific task, the scrum, is evaluated. Chapter 6 includes the description and development of a custom scrum ergometer required to quantify performance. The device was subsequently used to determine the technical contributors to scrummaging performance (Chapter 7). The final study (Chapter 8) determines whether the effects of fatigue experienced over a rugby game may affect the individual scrummaging performance.

In Chapter 9 the relevant data and new findings of individual technical performance are discussed with reference to previously reported studies. Performance guidelines are presented, along with a proposed model of rugby performance and possible avenues of application. This section scrutinises the strengths and limitations of the current studies and provides concluding remarks. Furthermore this section identifies possible future research ideas.

Chapter 10 includes the references used for the literature review in Chapter 1 and the general discussion in Chapter 9. The references for Chapters 2 to 8 are included as part of each study.



Figure I: The 1908 Olympic Gold Final contested between Australasia (Australia National Rugby Squad - light jersey) and Cornwall (Great Britain - hooped jersey). (Image from The John Corbett Davis Collection - State Library of NSW, Olympic Rugby Wallabies v Cornwall 1908, Out of copyright - Created before 1955).

Journal Submissions Emanating from the Work Presented in this Thesis

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Green A, Kerr S, Olivier B, Dafkin C, McKinon W. The trade-off between distance and accuracy in the Rugby Union place kick: a cross-sectional, descriptive study. *Kinesiology*. (Accepted for publication 2016).

Manuscripts under review:

Green A, Kerr S, Olivier B, Dafkin C, McKinon W. Rugby union players use different kinematic strategies in the running pass to achieve the same accuracy. *African Journal for Physical, Health Education, Recreation and Dance* (Under Review).

Green A, Kerr S, Olivier B, Dafkin C, McKinon W. Rugby ground passing kinematics: A side-on body orientation is more accurate than front-on body orientation. *South African Journal of Sports Medicine* (Under Review).

Green A, Kerr S, Olivier B, Dafkin C, McKinon W. A kinematic comparison of the rugby place and drop kick. *South African Journal for Research in Sport, Physical Education and Recreation*. (Under Review).

Green A, Kerr S, Olivier B, Dafkin C, McKinon W. A lower body height and wider stance are positively associated with the generation of individual scrummaging forces in rugby. *International Journal of Performance Analysis in Sport* (Under Review).

Green A, Kerr S, Olivier B, Dafkin C, Meiring R, McKinon W. Psychological and physiological fatigue does not correspond to decreased scrummaging performance over a simulated rugby match. *Journal of Sports Sciences* (Under Review).

Conference Presentations Emanating from the Work Presented in this Thesis

Green A., Kerr S., Dafkin C., Olivier B., McKinon W. Kinematics of back movement and lower limb power are related to the scrum force of individual rugby tight forward players. XXV Congress of the International Society of Biomechanics 12-16 July 2015. Glasgow, Scotland (Poster Presentation).

Green A., Kerr S., Dafkin C., Olivier B., McKinon W. The trade-off between distance and accuracy in the Rugby Union place kick: a cross-sectional, descriptive study. South African Sports Medicine Association Biennial Congress 19-21 October 2015. Johannesburg, South Africa. (Poster Presentation).

Contributions of Authors to the Projects

As part of the declaration of this thesis I acknowledge the contributions made by various individuals to the projects detailed in the sections below.

The experimental design for all works were devised by myself and my supervisors Samantha Kerr and Warrick McKinon.

All experimental data collection was performed by myself, in conjunction with my supervisors, Samantha Kerr and Warrick McKinon, and assisted by Chloe Dafkin, Benita Olivier and Rebecca Meiring.

All collected data was analysed by myself under the supervision of Samantha Kerr and Warrick McKinon.

Drafting of all works, including the literature review and original manuscripts, was undertaken by myself with guidance from my supervisors.

Algorithms for the kinematic processing were written by myself or modified using the code established by Warrick McKinon.

Construction of the individual scrummaging ergometer was done by myself, Warrick McKinon, with assistance from Mario Erkstein.

Chapter 1:

Introduction and Literature review

'Rugby Football is a game for gentlemen in all classes, but for no bad sportsman in any class'.

- W.J. Carey (and motto of Barbarians Rugby Club)

1.1 Introduction

A primary goal of a coach or of an applied sport scientist working in the sporting environment is to optimise the performance of the athletes in their charge in such a way that a team or individual has the best opportunity to achieve success. Performance in the team environment is a multifaceted variable that changes between sporting codes and disciplines. Additionally team performance can be considered the sum of individual contributions. Individual performance can be assessed on numerous levels ranging from technical and biomechanical skill to tactical play. The current literature on measuring sporting performance will be assessed with specific focus on performance in Rugby Union players.

A brief history regarding the development of Rugby Union to its meteoric rise to the current game played today will be presented, along with the changes in game play. The current game of rugby will be described including the tasks associated with rugby, the playing positions, how to score points and the potential injury risks. A general assessment of sporting performance is introduced, highlighting rugby performance. Sections devoted to various individual determinant of sports performance, including technical, morphological, physiological and mental parameters are discussed. Following which the rugby tasks performances are quantified and evaluated based on current literature. A brief description of fatigue and its effects on performance is presented. Finally the rationale and study objectives for this thesis are stated.

1.2 Brief history of Rugby Union

The development of football, from which rugby is derived, was haphazard as the public schools in England all had different rules for their field team-sports (Harvey, 2013). The two most prominent schools' rules were Cambridge, which would develop in to soccer and Rugby

school which inevitably developed into rugby in 1863. The game first played at Rugby school would not be recognised by modern observers as the game played today. That was until the legendary figure of William Web Ellis picked up the ball and advanced forward (Allison & MacLean, 2012; Harvey, 2013).

There have recently been conflicting reports regarding the event of William Web Ellis being the first player to advance with the ball in his hands, and creating the precursor to the modern game we know today (Allison & MacLean, 2012). The action that Webb Ellis took was not against the rules of the game and it is unlikely that he was the first person to do it (Allison & MacLean, 2012). It was however almost unthinkable to perform. In the early days, rugby teams were considerably larger than the 15 players per team today. The school house team at Rugby school would regularly exceed 200 players compared to their opposition of around 75 players of Rugby school day pupils (Allison & MacLean, 2012). The assumption that William Web Ellis advanced into this mass of players, refusing to lose possession of the ball, shows the courage and nature of the individual required to play rugby. It is likely that the myth surrounding William Webb Ellis does not accurately reflect historical events; rather he embodies the selflessness of the average rugby player. Allison & MacLean (2012) identify people responsible for the propagation of rugby from the school in Warwickshire to further aboard, where the game would further evolve.



Figure 1.1: A depiction of the football game played at Rugby School *circa* 1859. School house team illustrated wearing their customary white jerseys playing against the Rest of the school team in red. Note not only the number of players playing the game, but the number of players per team is not equal. (Credit: Rugby School).

Organised games of rugby football, outside of the public schooling system, would result in the general agreement and refinement of the rules. The rules of Rugby Football were defined and refined in 1871 by the top London clubs and the First Rugby board was established (Beneke, 2015). In the same year the first international match was contested between Scotland and England. In 1885 Rugby football underwent a code split after a disagreement between clubs regarding the payment of amateur players (Beneke, 2015). The two resulting codes of rugby were defined as Rugby Union and Rugby League. The split between the codes on the professionalism of players would have larger socioeconomic and national identity issues (Bauer and Vincent, 2015). The result is that the two codes have independently developed and diversified. The two codes differ in the manner of rules, style of gameplay and

number of players on the field. The most obvious feature relates to the manner in which play continues after the tackle. In Rugby Union the tackle is a contest for the ball, where in Rugby League the tackle is a means for the attacking team to play the ball. Rugby Union would remain an amateur sport until 1995 when the shift towards open professionalism was embraced.

The first Rugby World Cup was contested in 1987 by sixteen national teams. New Zealand were the inaugural hosts and champions. To date only four international sides (New Zealand, Australia, South Africa and England) have won the World Cup. World Rugby, the governing body of Rugby Union, states that rugby is played by over 4 million people in 105 different nations (World Rugby website), thus showing its worldwide reach and appeal.

1.3 The current game

It should be noted that rugby football is no longer a single sporting code and is composed of various forms including rugby league, rugby sevens, touch rugby, beach rugby, underwater rugby and wheelchair rugby. The current thesis focuses on the game of Rugby Union (which hereafter will simply be referred to as rugby). Rugby is a physical collision sport played for no longer than 80 minutes. Within a game of rugby, individuals compete in and attempt to score points or defend against an opposing team doing so. The objective of the game is to score points by either getting a try or kicking the ball between the opposing team's uprights. To do this, individuals in a team perform a wide variety of tasks including running with (carrying) the rugby ball, tackling, mauling, rucking, scrummaging, kicking, catching and passing a rugby ball. All of these tasks are defined in terms of rules set by the administering body, World Rugby and are administered by three officials, a referee on the field and two assistants on the opposing side-lines.

Over the years, rugby playing rules have been altered to improve player safety and enhance the nature of competition between teams. The changes in the laws have resulted in more collisions and ball-in-play time (Quarrie and Hopkins, 2007), which has inevitably altered the players' preparation. Quarrie and Hopkins (2007) reported the changes in body stature and general increase in body mass of rugby players over the years. Interestingly they noted that the increase is not similar in the general population, indicating that training and physical conditioning of the players has improved over the years. Currently players are heavier, stronger and faster than have every existed in the game. Today, it is conventional for a team to be comprised of specialist players with defined roles and often with differing abilities, suited to specific tasks. In the sections below I discuss this positional specialisation and then describe the unique features of the game of rugby in which these positional specialised players perform their distinct roles.

1.3.1 Playing positions

A rugby team is composed of 15 players divided into two main player types: forwards (eight players) and backs (seven players). These two sub-divisions are further divided into positional players. The group of forwards is composed of two props, a hooker, two locks, open and blind-side flankers and the number eight (Duthie et al., 2003). Backline players are composed of a scrum-half, a fly-half, two centres (inside and outside), two wings, and a fullback (Duthie et al., 2003). Individual descriptions of the playing positions are reported in more detail in Appendix 1.

Specialisation of playing position was first introduced by the All Blacks (New Zealand) for scrum positions in 1905 and by the 1970's specialisation of all positions was preferred by all local and international teams (Noakes & du Plessis,1996). The players are not only defined

by the tasks which they must perform, but normally have anthropometrical differences (Quarrie et al., 1996; Duthie et al., 2003). The anthropometrical differences are usually as a result of the tasks specific to the playing position. That is forwards perform the static high intensity tasks such as: mauls; rucks; line-outs; and scrums compared to the backs who perform the dynamics running tasks and make more tackles which are dispersed by longer rest periods (Jones et al., 2015; Lindsay et al., 2015). Forwards are generally heavier and taller than the backs, while players in the backline are generally faster than the forwards. The various tasks performed by the different playing positions are described in the next section.

1.3.2 Defining the features of a rugby game

The following section will briefly describe the tasks that are involved in a rugby game and the manner in which points may be scored. The tasks have been divided into two sections depending on the state of the phases of play. The phases can be defined by set pieces and restarts, and tasks that occur during open play.

1.3.2.1 Set pieces and restarts

Scrummaging

The scrum was designed as a method to quickly and fairly restart the game after a minor transgression, such as a knock-on, had occurred (World Rugby Laws of the Game). A scrum is composed of eight forward players, from both sides, who bind to each other in a physical shove for possession of the ball (Flavell et al., 2013; Preatoni et al., 2013; Swaminathan et al., 2016). The scrum-half from the non-transgression side will feed the ball into the scrum, where the opposing sides will either attempt to hook the ball backwards or attempt to push

their opponents off the ball using a combination of coordinated forces (Milburn, 1990; du Toit et al., 2004), combined mass (Preatoni et al., 2013) and muscular strength (Sharp et al., 2014).

Lineouts

If a player steps into touch along the length of the field, or if a ball is kicked out of the field along the length, a lineout will be used to restart the game. A line out is formed when players from opposing sides line up where the touch was found, a defined distance apart, to contest for the ball. The ball will be thrown in by the opposing side's hooker and both sides will contest by jumping/lifting potential catchers into the air (Trewartha et al. 2008, Sayers, 2011). During the contest no interference can be made to the player in the air or his supporters on the ground. Therefore the contest relies on the accuracy of the throw (Trewartha et al. 2008, Sayers, 2011; Croft et al., 2011), the height to which the jumper is lifted and the jumpers' catching abilities.

Set piece kicking (place kick)

The place kick is performed when a team is awarded a penalty or a conversion attempt (Padulo et al., 2013; Linthorne and Stokes, 2014). The ball is placed on a kicking tee, which is used to elevate the ball from the ground (Bezodis et al., 2007). The kicker will align the ball with their intended target (between the uprights) and use an individualised stepping sequence during their approach to the ball prior to making contact with the ball (Padulo et al., 2013; Cockcraft and van den Heever, 2016).

1.3.2.2 Open play tasks

Kicks from hand

Open play kicks are more dynamic than the place kick and usually occur in open play or in the case of the drop kick- as a method to restart the game and score points. Kicks made from hand include the drop kick, punts, high-ball kick, grubbers, and base kicks. The majority of these kicks (apart from the drop kick) will usually be made to gain field territory (Pavely et al., 2010). During kicks from hand, the ball is delivered to the kicking foot by the ipsilateral hand (Pavely et al., 2010). The kicks from hand include the following:

- *Drop kicks:* The drop kick is used to start the game or restart the game following the scoring of points. Similarly the drop kick can be used during open-phase as an attempted field goal. Briefly, the drop kick is performed by dropping the ball onto the turf and kicking the ball upon rebound. The oval shape of the ball requires the kicker to drop the ball as close to the apex as possible to ensure a good rebound. The drop kick is more dynamic in the sense that it requires the kicker to drop the ball onto the turf and make contact between the foot and the ball once the ball has rebounded upwards.
- *Punts*: The punt is primarily used to acquire an advantageous field position either when a team is on attack or during defence (Pavely et al., 2010). The kicker may intend to impart spin onto the ball for a spiral or torpedo kick, or may prefer an end-over-end tumbling action.
- *High balls/up-and-under*: The high ball or up-and-under is used to gain territory, but results in an in-air competition for the ball. The purpose of such a kick is to kick the ball on a steep trajectory and regain ball possession in playable space.

- *Grubbers:* A grubber kick is used to pierce the defensive line of the opposition. The ball is struck towards the upper half and results in an end-over-end tumbling action while the ball bounces on the turf. The bounce can occasionally be unpredictable, making it difficult for the potential receiver to catch.
- *Base kicks*: Base kicks are those performed from the base of a set piece, be it a scrum, maul or ruck. The scrum-half usually performs the base kick over the defensive line of the opposition while the attacking team chases the kick unimpeded. This kick can exhibit outcomes similar to the high ball or the grubber.

Passing: is the only way to advance in open play at speed while maintaining ball possession. When passing, the ball has to go backwards or laterally. i.e. the ball cannot be passed towards the opponents try line when passed between players (Pavely et al., 2009; Worsfold and Page, 2014). Two distinct passing types exists, namely the running pass and the ground pass. The running pass is performed between advancing players, while the ground pass is made from a static position at the base of a ruck or scrum.

Tackling: The only method in rugby to stop the opposing players from advancing is the tackle. A tackle can only be made on the player that is currently carrying the ball. The tackling player will attempt to wrap his arms around the advancing player, no higher than their shoulders, and safely bring them to ground (Posthumus and Viljoen, 2008; Quarrie and Hopkins, 2008; Gabbett, 2009; Austin et al., 2011; Hendricks et al., 2012).

Mauls: are formed when three or more players (ball-carrier and at least one player from each team) are involved in a contest for the ball, and the ball is held up off the ground (Posthumus and Viljoen, 2008). The maul is used as an attacking play to gain field territory while

maintaining ball possession. Contesting mauls requires the side with possession to protect the ball from the opposition while maintaining a steady forward momentum. The defending side will attempt to halt the maul by producing greater force or by safely and legally collapsing (sacking) the proceeding drive.

Rucks: are formed when a tackled player is brought to ground and the opposing teams contest for the ball (Posthumus and Viljoen, 2008). No hands are permitted for this contest and the players contesting for the ball must remain on their feet (Kraak and Welmen, 2014).

1.3.3 Scoring points in a rugby game

A game of rugby is won by the team that scores more points that their opponents. Therefore, the only direct method to determine a team's performance and supremacy over their opponents is through the quantification of points. Scoring point can be achieved through various methods: tries, conversion of tries, penalty kicks, drop kicks (field goals) or penalty tries.

1.3.3.1 The try and conversion

A try is awarded when a player manages to place the ball on or over their opponents try line. The try is currently worth five points and will be followed by a conversion attempting kick. It was named a try as it gives the team a 'try at goal' (successfully kicking the ball over the posts). Historically, a try was only conferred if the team could successfully achieve the conversion.

A conversion kick will be attempted following the awarding of a try. The conversion attempt will be taken by an elected player form the scoring side. They will be required to place the

ball along an imaginary line from where the ball was placed over the try line. There is no limit as to how far the kick can be taken from (although the kick cannot be taken from a distance closer than 10m from the try line, Padulo et al., 2013). The conversion is worth two points and the player has a total of sixty seconds to complete the attempt. A position that optimises the kick angle and distance is generally the underlying determinant of the attempt position (Padulo et al., 2013; Linthorne and Stokes, 2014). A successfully converted try is worth seven points.

1.3.3.2 Penalties

When a major transgression has occurred in open play the referee will award a penalty to the opposite side. They will have the choice as to whether they attempt a kick at the posts (currently worth three points), kick for territory or contest a scrum. If they kick for territory the kicker will punt the ball into touch, and the following lineout will be awarded to that team. If they decide to attempt a penalty goal, an elected player will attempt to kick the ball between the uprights and over the post, from the position of the transgression as defined by the referee. Try conversion and penalty goal attempts are performed when open play has ceased.

1.3.3.3 Drop kick

During open play, any individual may choose to attempt a drop-kick or field goal. If the ball successfully passes through the uprights and over the post, their team will be awarded three points. The drop kick is rarely used in the modern game; however numerous World Cup Finals have been decided on the success of a drop kick.

1.3.3.4 Penalty try

The final method of scoring points is through a penalty try. This is awarded when the defending side continually transgresses the laws or illegally prohibits a potential try from being scored. The result is five points (ultimately seven points, if the conversion is successful) awarded to the attacking team. Although currently the conversion attempt will be taken directly in front of the posts, the 2016 experimental laws award seven points to a penalty try, and eliminate the need for a conversion attempt.

1.3.3.5 Scoring points and winning strategies

There are potentially many different team strategies used to win a rugby game. These strategies are largely dependent on the individual skill level of the players, the geographical position and the atmospheric conditions of the match. Winning teams in the Northern Hemisphere perform better than the losing side, by scoring more points on entering the opponent's side of the field in the set phases of play (i.e. line-outs) and have the ability to maintain ball possession during the dynamics phases (Ortega et al., 2009). While in the Southern Hemisphere winning teams make fewer rucks, passing movements, complete fewer passes, made fewer errors, won more turnovers and mauls, made more tackles, and kicked more often (Vaz et al., 2010). While some differences exist between the two geographical styles of play it can be seen that ball possession and field territory are essential to potentially scoring points. Hughes et al. (2012) argued that simply quantifying the frequency of a task is not quantifying the entire team's performance as it neglects to account for position of play on the pitch, duration of the match, or pressure from the opposition.

1.3.4 Physiological demands of a rugby game

The game of rugby is a high impact sport where bouts of considerable anaerobic effort are interspersed with periods of high intensity sprints, active recovery and passive recovery (McLean, 1992; Deutsch et al., 1998; Roberts et al., 2008; Austin et al., 2011; Lacome et al., 2014). The physiological demands of rugby are not only dictated by the total distance covered during a game but are compounded by the additions of physical collisions and high intensity static components. Within a competitive match, a player can cover a distance of more than 4000m at various velocities (Duffield et al., 2012; Quarrie et al., 2013; Jones et al., 2015). This exertion requires players to have a high level of aerobic fitness and efficient physiological mechanisms to maintain a high level of performance in all the specialised aspects of the game (Deutsch et al., 1998; Spamer et al., 2009). The individual demands of playing rugby are related to the players' positions (Quarrie et al., 2013; Jones et al., 2015; Lindsay et al., 2015), with backs required to participant in dynamic aerobic events compared to the forwards' moderately static, high intensity activities. Additionally, the demands appear to be reliant on the team's position on the field and whether they are attacking or defending (Gabbett et al., 2014). The physical demands tend to be higher when a team is defending, which is likely to be related to the number of tackles a defending team must make (Gabbett et al., 2014).

The physiological demands can be divided into numerous categories. Those pertinent to this thesis are: velocity bands; energy metabolism, heart rates; and work rest ratio. This section will only summarise the physiological demands of rugby, with a detailed section on fatigue is presented in section 1.6.

Velocity bands of the individual players are currently assessed using individual GPS units worn by the players (Cunniffe et al., 2009; Cahill et al., 2013). This method allows for the velocity of the activity and the number of bouts (amount of time players enter a specific

velocity band) to be quantified for the individual players. There is however some contention around the measurement of the velocity bands, as maximal velocity attained in the match may not reflect the individuals' actual maximal running velocities. Additionally, the known differences in maximal running velocities apparent between backs and forwards may exclude forwards from attaining higher velocity bands. It may be more appropriated to report velocity bands as percentage of known maximal running velocity (Cahill et al., 2013). Velocity bands can be associated with the game play of the individual playing positions. Backs are most often associated with high intensity (dynamic) running and forwards linked to the high intensity, often isometric, static activities. This once again reflects the position specific demands of the game.

Backs are in open space more often allowing them to attain greater velocities and forwards are usually required to remain in close proximity to the ball which is linked to the physical collisions of tackles, rucks, mauls and scrums (Cahill et al., 2013; Lacome et al., 2013). This however does not restrict forwards to playing an expansive open, fast running game, it is just more likely that faster running speeds and high intensity runs are performed more frequently, and over larger distances, by the backs. Due to these positional specific demands, players of varying positions (forwards vs backs) are required to have individually refined physiological mechanisms.

Physiologically, the high intensity activities could result in the change in energy metabolism, from aerobic to anaerobic glycolysis and the accumulation of lactic acid and lactate (detailed in sections 1.4.6.3 and 1.6.2.1). Therefore, players are required to have refined aerobic and anaerobic mechanism to deal with the shifts in energy metabolism. The blood lactate usually peaks around 6.2-8.8 $mmol.l^{-1}$ (Deutsch et al., 1998; Duthie et al., 2003) during the game, but is usually lower than peak post-match as it is metabolised. It is likely that lactate is continuously produced and metabolised during the game and is largely dependent on when it

is measured. The accumulation of lactate has been reported to peak within the game (Deutsch et al., 1998; Duthie et al., 2003), although individual variation in the players and games are confounding variables.

Heart rates reflect the physical demands of the game with players spending a large proportion of the game in high heart rate percentages greater than 85% of maximal heart rate (Deutsch et al., 1998). Furthermore, the forwards spent significantly longer duration experiencing higher heart rates than the backs (Deutsch et al., 1998). The average values of heart rates have been reported around 170 beats per minute (Cunniffe et al., 2009). However, maximal heart rates will exceed this value as the intermittent nature of the game allows for brief moments of high intensity activity followed by active and passive recovery periods (Duthie et al., 2005; Roberts et al., 2008; Cunniffe et al., 2009). These periods have been quantified as the work rest ratio (McLean, 1992; Deutsch et al., 1998), and as with the overall gameplay differences between backs and forwards, the positional demands of rugby are evident in the work rest ratios.

The work to rest ratio is an indication of the amount of time that an individual will spend in passive recovery compared to the active workload (McLean, 1992). Backs have a higher work to rest ratio than forwards (Deutsch et al., 2007). Austin et al. (2011) reported that the front row players had the least amount of rest time in-between the repeated high intensity activities. These ratios indicate that the metabolic pathways for energy procurement are likely to be different between the playing positions. Furthermore the intensity of the work, although higher for forwards, will be interspersed by shorter rest periods. Quantifying the work to rest ratios and the physiological demands of rugby has led to the development of better training regimes for, and conditioning profiles of the players.

Interestingly the work rest ratio data presented by McLean (1992) and Lacome and colleagues., 2013 (reviewed by Duthie et al., 2003), prior to and following professionalism in rugby, may reflect improved training regimes in response to the increased intensity of the modern game. The high physiological loads and the repeated nature of the tasks within the game of rugby demands effective training regimes (Gabbett, 2015). However the intense collisions and high training loads of professional rugby may potentially lead to injury. Finally, the reported physiological demands of the playing positions and movement profiles of players can be used to develop more appropriate game simulations which will be discussed in section 1.4.9.

1.3.5 Injury risk

There are undoubtedly concerns for potential injury in rugby due to the high impacts and collisions that players experience in a game (McIntosh et al., 2010). The types of injury range from soft tissue damage to catastrophic spinal cord injury (Fuller et al., 2007; Brown et al., 2013). Although the majority of injuries are not catastrophic in nature they do result in time away from game play. The average injury incidence rates have been reported to be between 1.1 (for the lineout) and 10.5 (for a collision) injuries per 1000 events (Fuller et al., 2007). These values were reported for elite level professional rugby and there is potential for the rates to be higher in amateur players. The incidences of injuries are not equally distributed amongst the different playing positions. The most at risk player has been identified as the hooker (Wetzler et al., 1998; Fuller et al., 2007; Brown et al., 2013). This is due to the possibility of catastrophic events that can occur in the scrum.

The huge risk of injury is not only a concern for the participants, but is a concern to the success of any team. There has recently been a study that identified a negative association

between the injury burden (a quantitative measure of injury) and the number of points accrued during the season (Williams et al., 2015). The lack of continuity within the team and the likelihood of the team not comprising the best players were two notable reasons for the association.

Given the physiological demand, high risk of injury and pressure to succeed in a rugby game (financially, personally, politically etc.) there has been growing interest in studying rugby and methods to improve a team's chances of success by optimizing their performance. The following section will describe and assess different methods of quantifying and evaluating sporting performance.

1.4 Sporting performance and assessment of performance

The purpose of the literature review below is to evaluate the current methods used to quantify sports performance with respect to field based team-sports. The review will consider the different aspects of performance including inherent skills to the team and individuals. A general assessment of the use of kinematics, field tests and simulations will be made and will include discussion of the validity of their uses. To exhaustively describe performance in all sports is beyond the scope of this thesis. Therefore this section will discuss performance in the general context of sport and where relevant identify research particular to rugby.

1.4.1 Team performance

Performance in sport is ultimately reflected by the motto of the Olympic Games '*Faster, Higher, Stronger*'. Regardless of the nature of the sport in question, teams and individuals will incessantly strive to be better than their competitors.

In the current professional era, performance in sport does not only affect the result of individual games but can potentially affect the financial status of a team (Dimitropoulos and Limperopoulos 2014; Saraç and Zeren, 2013) or individual athlete. Consequently there is a need to assess and optimise performance beyond the physical conditioning of athletes. A more holistic approach encompassing all aspects of performance is required to maintain the elite profiles of teams. Rating performance in sport is ultimately defined by the outcome of the event: a finishing position in a race or the outcome of the match (winning or losing). The skill of individuals in conducting specific tasks, which accumulate into team effort, can be assessed by quantifying and evaluating the execution of the specific skills required to perform the sport. Therefore in order to better assess team performance a set of sport specific performance parameters are needed. That is to go beyond the general morphological, physiological, tactical and technical approaches and become more sports specific, if not positional specific in the approaches to quantifying and evaluating performance in sports. These approaches can be divided into team based and individual based assessments. The descriptions and evaluations of team and individual assessments are provided hereafter.

1.4.2 Measuring performance in team sports

A high level of individual performance may not necessarily result in a team's success. This may be due to an even better performance by the opposition or due to a lack of cohesion and coordination of individuals in a team. Only when the interactions between the individual performances, where efforts are complimentary, can team performance be maximised. That

said an approach known as notational analysis has been developed which, while keeping the above caveat in mind, may begin to be able to quantify the summed performances of individuals in a team and in so doing, may give an indication of a team's performance as being a collective sum of individual performances (Hughes and Bartlett, 2002).

Notational analysis is the objective reporting and quantification of key components of performance in a valid and consistent manner (Neville et al., 2008). The application of notational analysis has allowed for the development of more specific coaching and training regimes. Additionally strengths and weaknesses of the teams and their individuals can be identified. Notational analysis has become more sophisticated with the development of the personal computer (Hughes, 1988) resulting in faster analyses of larger datasets. Notational analysis has been applied to various disciplines of sport, from racquet sports (O'Donoghue and Ingram, 2001) to team sports such as handball (Rudelsdorfer et al., 2014) and basketball (Lorenzo et al., 2010) and more specifically field-based team sports. While notational analysis is usually used to assess the quantity and quality of task performance, it can be specifically applied to the locomotion and intensity of locomotion during the match.

Motion analysis (in this context) refers to the type, intensity and duration of locomotive activities during sport (Reilly, 2001). The analysis of motion in sport has developed from laborious video analysis (Duthie et al., 2005; Deutsch et al., 2007; Roberts et al., 2008) to semi-automated global positioning systems (GPS) worn by players (Cunniffe et al., 2009; Cahill et al., 2013). Motion analysis is often used to quantify player workload (Deutsch et al., 2007) and evaluate individual performance (Cahill et al., 2013; Gabbett et al., 2014; reviewed by Cummins et al., 2013). GPS data has been reported for a wide variety of field-based team sports (Cummins et al., 2013) with the majority of these studies assessing the work rate velocities and distances covered by individuals during a game.

1.4.2.1 Assessing team performance in rugby

Performance in rugby ultimately reflects the ability of one team to score more points than another (Ortega et al., 2009; Vaz et al., 2010; Hughes et al., 2012). The most advantageous method to scoring points is through a try. Previous research has shown that winning teams are normally those that have scored the most tries (Ortega et al., 2009; Hughes et al., 2012). However the process of the game that eventually leads to a try is complex, involving many intermediate steps. Because of this complexity Jones et al. (2008) developed a series of performance indicators that made it possible to objectively rate a team's performance throughout a rugby game. While this is a method of objectively rating a team's performance it is not without faults (James et al., 2005; Jones et al., 2008; Hughes et al., 2012). The match outcome is not solely based on the performance of the winning team, and can therefore change between matches and even within matches. Teams would rarely play to their opponent's strengths, and would rather exploit their opponent's weaknesses to their own advantage.

Regardless of the sport, match data can be misleading if the team's performance has not been assessed longitudinally (Hughes and Bartlett, 2002, Hughes et al., 2012**,** Kempton et al 2013). Another limitation of such notational analyses is the inability of the quantification of the opponents as the outcome of the game is largely dependent on the performance of the opponents.

A key aspect of notational analysis is the quantification of pertinent aspects to the overall performance of the team. However in field-based team sports a number of tasks key to the entire team's chances of match success are performed by individuals. Therefore the individual assessment of a player's ability to perform is necessarily linked to team success and is unavoidably a major driver of team sports performance.

1.4.3 Individual performance within teams

There are various methods to determine individual performance, ranging from technical to physiological and psychological testing. Assessing individual performance within a team environment is confounded by many additional factors. This necessitates quantification and assessment of positional dependent parameters regarding the individual's performance. Therefore key performance indices have been established for invasion type team sports and are specifically applied to individual playing positions (Hughes et al., 2012). When these key performance indices were applied to soccer, commonalities between the playing positions were reported (Hughes et al., 2012). It was noted that key performance indices were based on tactical, technical, physiological, and psychological performance parameters.

Similar to team performance, individuals can be assessed based on their efficacy of tasks within the game. To this end the application of notational analysis has been applied. However while individual brilliance can result in the team successfully beating their opponents, the majority of successful team performances may also originate from the contributions of individuals and, to a further extent, the interplay between individuals. Therefore individual skill assessment should preferably include the study of factors which gauge the ability of individuals to cooperate (Hughes and Bartlett, 2002). While such an approach is logically based it suffers from being potentially highly artificial.

1.4.3.1 Assessing individual performance in rugby

It can be argued that a team's performance cannot simply be determined by the sum of all tasks executed within a game. The difficulty with the assessment of team's performance within rugby arises as rugby is a complex game composed of tasks that are open and closed in nature. Furthermore the positional play requires individuals to perform different tasks of

varying intensities (James et al., 2005; Jones et al., 2015). Using the approach of assessing an indirect index of performance in an individual (an approach that is often used in the current thesis) one must first identify a trait, or combination of traits which is likely to reflect superior performance. Consequently James et al. (2005) devised a series of indices to rate the performance of individuals. Their performances of the tasks were based on successful and unsuccessful behaviours of the individual performance indicators (James et al., 2005). The 15 players are normally divided into 10 playing clusters, which include: props, hooker, locks, openside flanker, blindside flanker, number 8, scrumhalf, outside-halves, centre and outside-backs (James et al., 2005). The 10 playing cluster indicate that the positions require different abilities to perform the various positional-specific tasks. The position-specific performance indicators were as follows (James et al., 2005):

- The hooker was rated based on the success of their lineout throws.
- Locks were rated based on their lineout takes, and securing the ball following a restart.
- Back row players (openside flanker, blindside flanker, number 8) were rated on their ability to secure the ball at a ruck (perform a turnover).
- Players in the backline were assessed on their ability to successfully perform kicks.
- The outside backs, in conjunction with their ability to kick, were assessed on their ability to successfully catch the high ball.

While tasks may be specific to the playing position there are numerous tasks that have an overlap between playing positions (James et al., 2005). Performance indicators common to all playing positions include tackles, carries and passes. An overall positive performance

predictor is the ability to score a try. Negative performance predictors common to all playing positions include penalties conceded and handling errors.

1.4.3.2 Assessing the unit performance in rugby

There must be an intermediate step in the performance between individual performance and team performance. Hughes et al. (2012) suggested that the performance of individuals within smaller groups through the phases of play, namely unit performance, should be quantified. A unit of individuals can be considered as the smaller groups of players that perform tasks requiring two or more players. By describing these units one would be able to better identify the performance of a team when it comes to how well a forward pack scrummages; player units lift in the line-out and on restarts; perform in defence; defend or attack in mauls and rucks; and finally the interplay between the players during set moves or planned running lines. The relevance of this is that the majority of team performance predictors (turnovers won, scrum line-out success) are executed as individuals, or individuals acting in small unit groups. From this we can see that overall team's performance can be directly attributed to the units and ultimately the individuals. Therefore the individual performance of every player should be scrutinised and optimised.

The identification of these performance indices are indirect and only theoretically contribute to a team's success. That is, it may sometimes be possible that the teams with ineffectual execution of the various rugby tasks can potentially win the game due to another factor or set of presumably quantifiable factors which could be studied. Furthermore the use of such performance indices do not account for external factors such as the weather, or more unpredictable events like the bounce of the ball and the unknown decisions to be made by the referees (Jones et al., 2008).

The assessment of performance in rugby is largely dependent on the use of notational analyses. Hughes et al (2012) mentioned that a dynamically complex game like rugby far exceeds the simple analysis of incidence data. As with all notational analyses the interaction between players cannot be measured, nor can the situational awareness. One such study attempting to assess the interaction between players has used mathematical models to quantify the complexities of decision making in rugby passes. Diniz, Barreiros and Passos (2014) modelled that the decision to pass is determined by the velocity of the defender and ball carrier and the distances between the defender and ball carrier. If the defender exhibited more velocity than the ball carrier, the ball would be passed to the supporting player. Additionally, this decision was calculated to occur relatively close to the defending player (Diniz et al., 2014). This study displays the necessary level of investigation into the individual performances of players and therefore additional studies with this depth of analysis are required.

Travassos and colleagues (2013) argued that a major limitation to the current analyses of sports performance is that they focus on distinct actions and consider the action to work in isolation. In an attempt to further capture the likely usefulness of team play dynamics over the assessments of individual players against potentially unrealistic artificial indices of performance, future studies are required to assess the interplay between players, specifically the spatial awareness and positional play of individual players. The analysis of the interplay between individuals and groups of individuals is extremely complex as the interplay can have many different permutations. Data mining is a possible method to elucidate these patterns (Ofoghi et al., 2013). Data mining has been understudied in the context of sport and could possibly be used to identify the defining features of winning multifaceted team sports. However data mining requires vast amounts of data to detect relationships. While the

executions of such studies are feasible they may be limited by the processing abilities of current devices.

The preceding sections have focussed broadly on the topic of performance analysis in sport, highlighting examples from rugby. In the sections below I introduce the literature related to the individual measures of performances that are relevant to the current thesis.

1.4.4 Measuring technical skill

The assessment of sports skill and technical skill has been determine using the notational methods (described above) and more objectively been achieved through biomechanical methods (Lees, 1999). Kinematics in particular has been applied to optimise technical performance while reducing the injury occurrences in various sports disciplines (Glazier and Davids, 2009). A major component in the determination of performance in the current thesis is the use of kinematics. Therefore the following section will briefly describe the background to the development of kinematic models.

1.4.4.1 Development of kinematic models

Movement during physical actions and the beginning of human movement analysis were initiated by Eadweard Muybridge in 1887 when the series of images entitled *'Animal Locomotion'* was developed. Within this series of images are the depictions of daily activities such as washing, walking, manual labour tasks and sporting activities. Figure 1.2 is one such example of a sporting activity, depicting a man running, presumably sprinting.

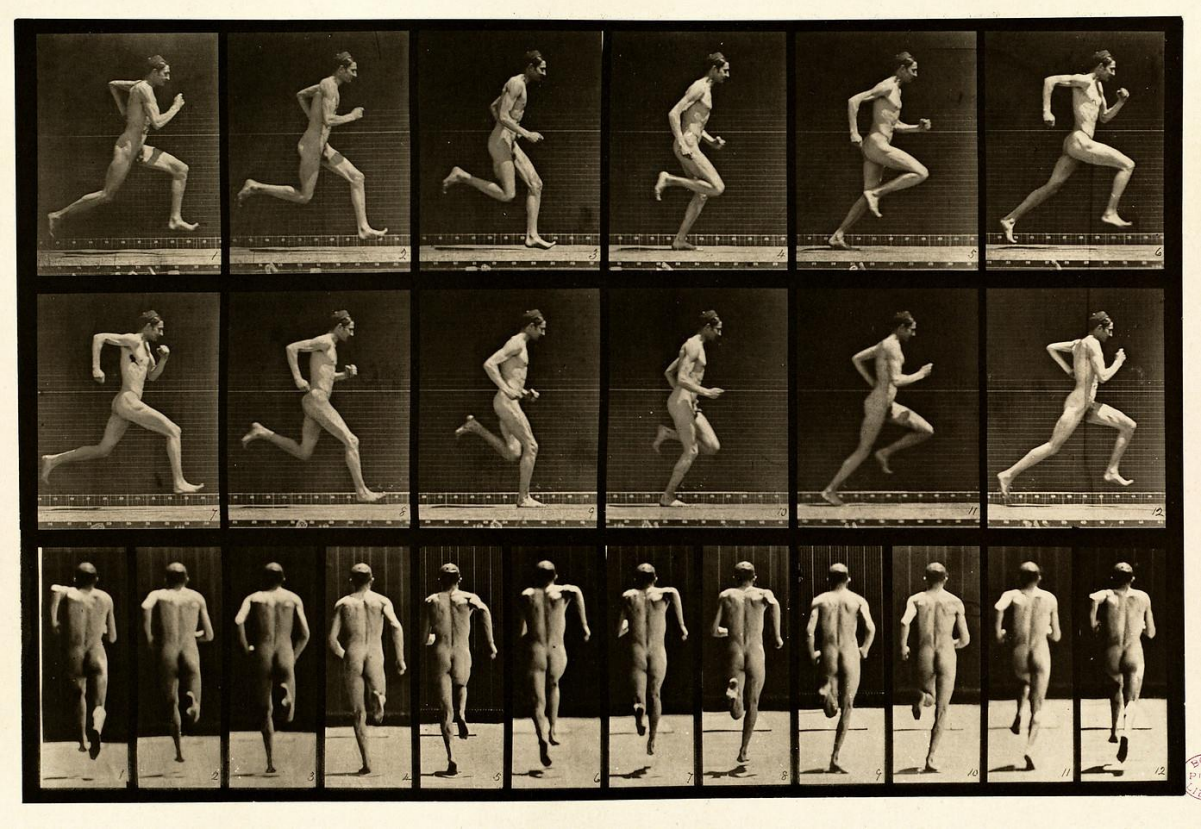


Figure 1.2: A sequential depiction of a running man plate 62 from the first volume of Eadweard Muybridge's "Animal Locomotion" (Muybridge, 1957).

Further advances to the investigation of movement resulted from the development of the ‘chronophotographic gun’ in 1882 by Etienne-Jules Marey. The use of such a device allowed for multiple images of rapid succession to be developed on a single photograph and was used to record sporting action in the 1894 publication of ‘*Le Mouvement’* (Figure 1.3).

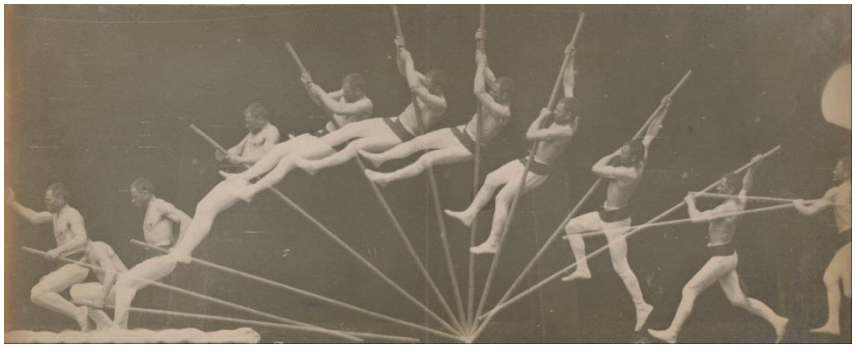


Figure 1.3: Superimposed sequential sequence of a man vaulting

Title (English): Movements in Pole Vaulting by Étienne-Jules Marey (1830–1904)

The development of the Direct Linear Transformation (DLT) by Abdel-Aziz and Karara (1971) allowed for the three-dimensional recreation of points recorded by multiple two-dimensional cameras and has since revolutionised the way kinematic data is captured and analysed. With the advent of digital image processing in modern times however, kinematic analysis has undergone radical changes since the development of modern digital kinematics over 30 years ago (Lees, 1999; Glazier and Davids, 2009). The most popular method of assessing technical performance is through two-dimensional (2-D) or three dimensions (3-D) video analysis (Lees, 1999; Lees, 2002; Glazier and Davids, 2009), although 3-D analysis provides a better representation of the movement (Glazier and Davids, 2009). A 3-D analysis requires a kinematic model that can accurately embody the movement of the individual.

Most current systems make use of a marker set to represent the limits of the limb segments or establish the local coordinate system (Kadaba et al., 1990; Gutierrez et al., 2003). Limb segments are represented by simple rigid lengths of uniform density (Glazier and Davids, 2009). Individual segments will be assigned their centre of mass position along the length of the primary axis (Gutierrez et al., 2003). Similarly the positions of the joint centres are calculated through the use of mathematics based on cadaveric or other data (Kadaba et al.,

1990; Gutierrez et al., 2003). The joints are predominantly defined as simple frictionless hinges (Glazier and Davids, 2009). Ideally the joint should be defined by the anatomical range of motion even though, as Glazier and Davids (2009) mentioned, in their assessment of human motion, mechanical constraints cannot fully represent the biological controls. The development of more representative joints has occurred to varying success.

The mathematical representation of the body in space allows for the calculation of angles of limbs relative to one another. Similarly it allows for the joint angular velocities and segmental momentums to be calculated (Lees, 1999) when segmental inertial parameters are used (de Leva, 1996).

However discord in the degree of model sophistication is present between scientists, although the resulting model is usually determined by the research question of the individual studies (Glazier and Davids, 2009). The more complex the representing mathematical model the more accurate and valid the outcomes (Glazier and Davids, 2009). However the very tailoring of the model may present with differences in potential outcomes. Movement variability is large not only between individuals but within individuals. Therefore individual-specific models may be useful in the assessment of intra-individual movement variability, but may impede the assessment of general movement patterns. Hughes and Bartlett (2002) suggest that in an attempt to reduce the effects of inter-individual variability that biomechanical assessments of individual skill must be compared with individuals of similar skill level.

Deterministic models have also been used to assess technical performance of sports (Lees, 1999; Chow and Knudson, 2011). A deterministic model defines the outcomes of performance and seeks to identify the mechanical factors that could possibly affect performance outcomes (Lees, 1999). This approach is methodical and is thought to be a useful tool to discover the most vital single predictor of the performance (Lees, 1999; Chow

and Knudson, 2011). However Lees (2002), and more recently Glazier and Robins (2012), commented that deterministic models are models of performance and not the technique used to achieve performance.

Current kinematic models used in the investigation of rugby performance include 2D assessments (Sayers 2007; Padulo et al., 2013) and 3D assessments (Bezodis et al., 2007; Saletti et al., 2013; Cazzola et al., 2014). Of these assessments many investigators use custom algorithms and models to assess specific movements of bodily structures. Of the many kinematic parameters, two (the kinetic chain and the whole body centre of mass) are a particular interest in the studies of this thesis.

The kinetic chain

The use of kinematic models in the investigation of sports has revealed that the sequencing of the limbs may have an effect on the individual joints, or segments that are linked. The imparting of sequentially higher velocities between segments in a proximal to distal fashion is known as the kinetic chain sequence (Lees, 2002). Arguably the biggest advantage of the kinetic chain is the development and transfer of velocity between the segments allowing for segments further along the chain to have larger initial velocities than the previous segment (Figure 1.4). The effectiveness of the kinetic chain can be a performance indicator in numerous actions. Throwing (Fleisig et al., 1996), kicking (Lees et al., 2010; Naito et al., 2012), racquet (Elliott, 2006) and club sports (Milburn, 1982) are all enhanced through the application and optimisation of segmental sequencing, specifically the kinetic chain.

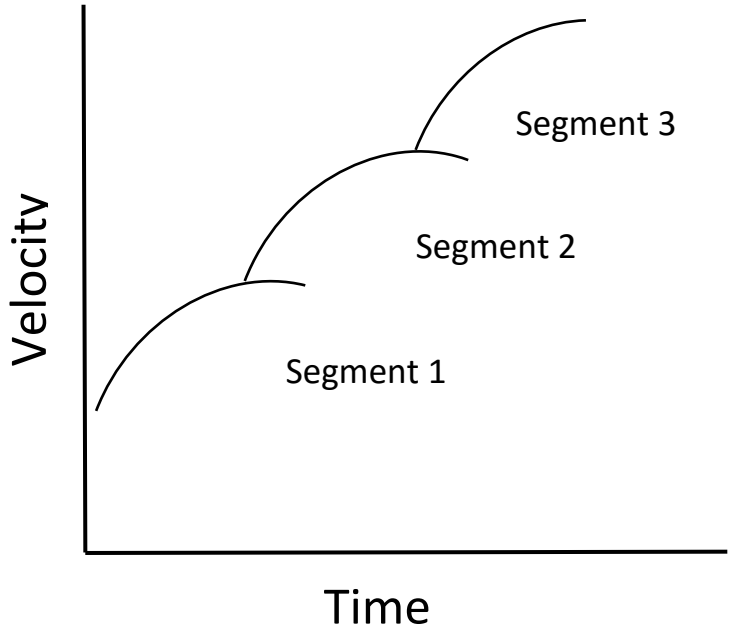


Figure 1.4: A representation of the interaction and transfer of velocity between segments in the kinetic chain.

The whole body centre of mass

The position of the whole body centre of mass (CoM) is defined as the point at which the mass of the entire body is concentrated. Kinematic measurement using segmental analysis is considered the best technique to determine the CoM location (Lenzi et al., 2003 and Gutierrez-Farewik et al., 2006). This technique makes use of geometric shapes which represent the body segments (Erdmann, 1997 and Gutierrez-Farewik et al., 2006), and the positions of the segment's CoM are calculated through datasets of segmental inertial properties (Dempster and Gaugharn, 1967; de Leva et al., 1996). The resulting CoM location is therefore determined by the sizes, compositions and positions of the segments. The CoM position is dynamic as the movement of the limbs (and their own CoM position) causes the

shifting of the whole body CoM. However the CoM location is estimated to be around the level of the sacral vertebrae (McKinon et al., 2004). Within the context of rugby performance, the location of the CoM is relevant for the following reasons: agility to perform cutting manoeuvres (Wheeler and Sayers, 2010), stopping the ball carrier through tackles (Hendricks et al., 2012), and to a large extent in the performance of passing (Worsfold and Page, 2014), kicking (Zago et al., 2014) and scrummaging (Sayers, 2007; Cazzola et al., 2014; Preatoni et al., 2015).

1.4.5 Morphological predictors of performance

Although the focus of the current thesis is on skill, the ability to perform these skills is at least in part dependent on the inherent and trainable traits that are available to the rugby player. These morphological features of performance will arise when discussing rugby performance in the sections that follow, but some general features of the anatomy of performance are worth noting here.

Morphological predictors of performance are intrinsic to the nature of the sporting event. In fact, Olds (2001) suggested that sports can be identified as Darwinian systems that select specific traits that directly relate to performance. That is power orientated athletes (Watts et al., 2012; Sedeaud et al., 2014) exhibit different morphological parameters to endurance orientated athletes (Sedeaud et al., 2014; Stanula and Roczniok 2013). Team sports (Helgerud et al., 2001) usually display homogeneous body types amongst the individuals. Contrary to this, body types in rugby player are highly variable compared to other sporting codes. The major reason for the large range of morphology is due to the different positional demands within the game (Lee et al., 1997; Quarrie and Wilson, 2000; Duthie et al., 2003; King et al., 2005; Quarrie and Hopkins, 2007).

Overall, rugby players are bigger in stature and have larger body segments than the general population (Olds, 2001 Lovell et al., 2013). The increase in body stature and mass has increased in rugby player at a disproportional rate to the general population over recent years (Quarrie and Hopkins, 2007). The increase in body size and mass may indicate that the selection pressures of rugby have resulted in bigger and heavier players being selected at the highest playing levels (Quarrie and Hopkins, 2007; Fuller et al., 2013), so much so that taller and heavier teams have been associated with success (Olds, 2001; Sedeaud et al., 2012). At lower playing levels there seems to be less emphasis placed on body size and composition (Duthie et al., 2003). Although the smaller range of differences between backs and forwards at the lower levels of play may be attributable to the similar training regimes between the backs and forwards, and lack of training specificity (Smart et al., 2013).

1.4.6 Physiological predictors of performance

Comparable to the argument for anatomical facilitation of skill, athletes who are able to display a predisposition for physiological parameters such as: strength, speed, supply of energy needed for performance, and the ability to coordinate skill may be better performers. All of these characteristics will depend on the optimisation of different physiological systems, which in turn could improve overall individual performance.

1.4.6.1 Strength

The level of muscular strength is largely dependent on the tasks within the sport of interest. McMaster et al. (2014) summarised that maximal strength has a wide range of values based on the specific training nature of sport. Competitive sportsmen exhibit greater strength than trained (non-competitive) individuals.

As described in the preceding section on morphological attributes there is a tendency for rugby coaches to select physically bigger players. One likely reason for this is due to the probability of the larger player dominating the collisions. Similarly, larger players may have more muscular strength (McMaster et al., 2014). Therefore player strength is essential in a contact sport for the collisions experienced during tackling (Speranza et al., 2016), scrummaging (Quarrie and Wilson, 2000; Sharp et al., 2014), mauling and rucking. However the application of muscular strength is not limited to the performances of these tasks. Effective sprinting, jumping, lifting and more refined tasks such as kicking (Manolopoulos et al., 2013) all require competent levels of muscular strength.

Comparisons within rugby players have revealed that the forwards have been associated with greater muscular strength than the backs (Duthie et al., 2003). Durandt et al. (2006) reported that pure muscular strength was significantly higher in junior age-group level playing rugby forwards compared to backs. However the difference was absent when accounting for body mass, indicating that rugby regardless of the playing position, requires a large amount of muscular strength.

1.4.6.2 Running speed

The running speed of players to occupy space is a skill required by all individuals in field based team sports. However unlike timed racing events speed does not reflect overall performance. In field based team sports the ability to occupy open space is vital to the team's ability to play more freely. Teams may benefit if players can occupy the open space at a faster rate than their opposition. Thus, it may be beneficial for individuals to have the ability to accelerate and maintain a high velocity over a period of time. Indeed soccer and hockey

players have been shown to frequently enter velocity bands that exhibit sprinting (Cummins et al., 2013).

Within the context of rugby, once again the positional demand dictates the abilities of the player. Therefore distributions of speed between players are not equal and disparities between forwards and backs are present (Duthie et al., 2006; Gabbett, Kelly and Pezet, 2008; Jones et al., 2015). Even within a more homogenous sample of rugby league players the positional differences between the running speeds of backs and forwards is still apparent (Kirkpatrick and Comfort, 2013; Till et al., 2014). This may indicate the maximal velocity of the individual is related to their other factors that determine their positional play.

1.4.6.3 Energy metabolism

Jeukendrup (2012) summarised that energy metabolism is one of the leading contributors to performance in sports, and that the manipulation of such factors can lead to the improvements of sports performance. Optimal energy is produced through aerobic pathways; therefore, the measurement of oxygen consumption is of major significance in sports performance. VO_2 refers to the measurement of oxygen consumption. Therefore the maximal rate of oxygen consumption is defined as VO_{2max}. The measurement of VO_{2max} is closely associated with the limits of the cardiorespiratory system, specifically the transportation of oxygen (Hawkins et al., 2007). VO_{2max} has been reported as an indicator of performance in endurance athletes (Shaw et al., 2015; Tønnessen et al., 2015). Thus, having a more efficient aerobic system can predispose an individual for endurance events. While there is a need to have a developed aerobic system the nature of field team sports is not continuous at a set intensity and are intermittently dispersed with recovery periods. Aerobic training in soccer players has been

shown to increase their VO_{2max} and improve match performance, by increasing total distance covered during a game and increasing time on the ball (Helgerud et al., 2001).

Specific to rugby, forwards have been reported to have lower VO_{2max} values than backs (Scott et al., 2003; Jarvis et al., 2009). These results, on the surface, may indicate that the demands of the different playing positions may influence the oxygen utilisation of the individuals, with backs involved in more continuous running than forwards. However the differences may not be due to the underlying mechanism of oxygen consumption, but may be attributable to the differences in body size and composition between the two groups of players (Scott et al., 2003). Body size and more specifically the composition of the body may be more differentiating factors of the disparity in VO_{2max} values. The percentage of muscle mass has been reported to be higher in in backs compared with forwards, who have higher body fat percentages (Duthie et al., 2003; Scott et al., 2003). The higher adipose tissue value does not actively contribute to the performance (Jarvis et al., 2009). It is likely that if VO_{2max} is determined for unit muscle mass that the lower values in forwards may disappear.

The quantifiable value of VO_{2max} is however not static. Gabbett (2005) showed that VO_{2max} declined in rugby players during the extended rugby league season, and attributed the VO_{2max} decline to the reduction in training loads. Therefore in order to maintain the level of VO_{2max} requires continual aerobic training. Unlike soccer, rugby is more stop-start in the nature of gameplay and it is likely that while aerobic fitness and performance are required for the game of rugby, they may not be specific performance predictors. Consequently, Duthie and colleagues (2003) suggested that VO_{2max} is not the defining physiological predictor of rugby performance and is instead a component in the required fitness profile.

Players need proficient mechanisms to deal with increasing levels of lactic acid and mechanisms that can effectively metabolise lactate as an energy substrate. The accumulation

of lactic acid and the substrate lactate will be discussed in section 1.6.2.1 with specific focus on the development of fatigue.

1.4.6.4 Coordination

All sporting codes require a level of coordination, specifically the coordination from visual input (foot/hand-eye coordination) and inter-segmental coordination. The coordination between the visual stimulus and physical action of the hand can be valuable in prediction of the future ball position as it reflects the ability to successfully catch or receive the ball.

The coordination of limb segments is essential to the performance of tasks as it controls the velocity of the segments during the kinematic sequence that is the kinetic chain (Lees et al., 2010). Additionally the need for dynamic coordinative control is necessary in ball sports, where running and ball control are essential to performance. This is displayed in the control of the ball in hockey and soccer, by dribbling while running and the eventual striking of the ball through the optimised kinetic sequence (Zago et al., 2016). Similarly the coordination of the running sequence, while performing these tasks can ultimately affect the degree to which the task is executed.

These physiological drivers of athletic performance will arise when discussing rugby performance in the sections (sub-sections of 1.5) that follow. Note that, as is the case for skill but unlike the case for morphology, for the most part, changes in physiology are to an extent easily trainable and may be improved through physical preparation. An additional facet that could affect performance is the mental state of the individual or the combined team.

1.4.7 Mental state and psychological predictors of performance

Better performance has been linked to the positive state of mind prior to the event (Prapavessis, 2000). Similarly an athlete may be considered for team selection based on their ability to cope with the pressure of performing at a high level (Prapavessis, 2000). The ability to cope with the physical and emotional demands of competition is essential to the success of an individual. Higher-level athletes experience less cognitive disturbance prior to (or can be understood as better emotional control: ability to reduce the effects of emotions on physical performances) a competitive game than lower-level athlete (rugby players in this instance) (Golby & Sheard, 2004; Andrew et al., 2007; Robazza & Bortoli, 2007). Equally the performance of a team can be attributed to the mood states of individuals and it seems to be a bidirectional relationship between the individuals and the team (Totterdell, 2000). Mood or mental state is a qualitative indication of the emotional wellbeing of the individual. The mental state of an individual is likely to be dependent on the emotional intelligence of the person and their ability to cope in potentially stressful situations. Theoretically better performers are more likely to maintain good performances regardless of the situation. Mental state can be assessed using a series of words defined within the Profile of Mood State Questionnaire (POMS). The POMS was developed by McNair in 1971 and has been reported to be a good measure of fluctuations in mood during or following exercise (Berger and Motl, 2000). Questions are valued between 1 and 5 and a score is calculated through the use of an equation. The resulting mood disturbance profile can then assess the effects of mental disturbances on performance (Berger and Motl, 2000; Mashiko et al., 2004). One major concern with using a scale based on specific words is connotations of the words may have different implications between individuals. Additionally changes in mood state and response to exercise are highly individualised (Berger and Motl, 2000).

Players' emotions can influence their performances (Robazza & Bortoli, 2007; Campo et al., 2016). Furthermore, the influence of emotions may not be unidirectional, that is, emotions may not only affect performance, but rather a bi-directional relationship between performance and emotions may exist (Kerr & van Schaik, 1995; Polman et al., 2007; Robazza & Bortoli, 2007; Campo et al., 2016). Where emotions that are associated with good performances reinforce the performance, and negative performance evoke negative emotions, which in-turn, perpetuate a reduction in performance. This aspect may be best describe by the term "form players", players that exhibit their best performance when their self-confidence is highest.

One method utilised in sport to improve performance is the setting of performance goals. Mellalieu et al. (2006) assessed the effects of goal setting on the effectiveness of various tasks performed in rugby union players over a period of 20 games. The first ten games were considered as pre-intervention data. The intervention consisted of meeting with the five experienced players and assessing their previous performance followed by player-driven improvement goals. Following the intervention improvements in the team's performances, indicated by more game wins and improved winning margins, were observed (Mellalieu et al., 2006).

Another method is the use of mental imagery which, has been associated with improved self-confidence and reduced anxiety prior to a competitive rugby game. (Mellalieu et al., 2009). Mental imagery is not only used prior to a game, but can be utilise successfully within a game. Specifically, this technique used by players in rugby, prior to attempting a place kick, is to visualise a successful kick. Jackson and Baker (2001) reported that an international fly-half would focus on attaining a positive mind-set prior to performing an attempt at goal. A major concern with the use of psychological assessments of performance is that all people react differently to different emotional situations. Emotions are difficult to quantify and even

more difficult to assess. Furthermore the dynamic nature of sports may cause a rapid change in emotional state to occur. Therefore individuals that are less prone to extreme emotional fluctuations are probably more likely to succeed under dynamic emotional tasks.

1.4.8 Application and validity of field testing

Laboratory testing has the advantage of scientific reliability as many parameters that may affect performance can be controlled. However the one factor that a laboratory test excludes is the environment where the game or tasks are usually performed. A second problem with laboratory testing is the unrealistic duration of the laboratory testing compared to the actual field performances they are designed to emulated or assess. Ideally an investigator would want to establish a laboratory that mimics the exact environment of the sport in question, or move their laboratory to the environment of the sport. While the latter would be a logistical nightmare, a laboratory could technically be mimicked by assessing performance using simplified field tasks.

While the use of spirometry in the laboratory setting may be more accurate than simplified field tests (Metaxas et al., 2005), the Yo-Yo intermediate test, a field based test, has been reported to be a predictor of aerobic fitness in soccer. The test elicited aerobic and anaerobic demands that were expected to develop within a soccer game (Krustrup et al., 2003). The Yo-Yo intermediate test has been applied to many different sporting codes that required continuous aerobic and anaerobic performances (Sirotic and Coutts, 2007).

A major positive for the yo-yo test is easy to implement, with minimal use of equipment and the application of the test in the same environments as training sessions or competitive matches. Furthermore, the test can accommodate numerous players at once. Moreover, the yo-yo has high ecological validity and is easily repeatable (Krustrup et al., 2003; Krustrup et

al., 2006; Krustrup et al., 2012; Austin et al., 2013). Participants are not required to leave the familiar settings (practice or match facilities) to participate. The yo-yo test has been reported to be reliable in determining the aerobic demands of intermittent sports (Krustrup et al., 2003; Currell & Jeukendrup, 2008). Additionally, the distance covered by the participants can closely mimic those experienced by the players (Austin et al., 2013) and officials (Krustrup et al., 2012) during a competitive game, depending on the derivative of the yo-yo test. Ideally a yo-yo test or derivative thereof will mimic the physiological demands (aerobics and anaerobic) of a competitive game, in term of the distance covered. Similarly, tests should be intermittently dispersed to replicate the stop/start nature of the sport. (Atkins, 2006). To overcome this limitation, various adjustments have been made to include changes in direction (Krustrup et al., 2012), and the inclusion of specifics related to the sporting codes (BURST in the cases of rugby). However, this test was specifically designed to simulate rugby and with be discussed in the proceeding section on match simulations. Research has shown that tests designed around the time-motion analysis data better reflect the in-game demands (Currell & Jeukendrup, 2008; Roberts et al., 2010; Austin et al., 2013). These tests have allowed for the design of fatigue interventions and better development of specific training regimes, and therefore remain essential to the study of intermittent team sports. Another widely used field test is the vertical jump test. The vertical jump is a simple method to determine the lower body power (Baker, 1996; Gabbett, Jenkins & Abernethy, 2011b). The test requires participants to crouch down and jump as high as possible. They attempt to reach out with their arm to attain a maximal height. The measurement is derived from the difference of their reach height and maximal jump height. There are various additions to the vertical jump which may permit the use of arms to generate more force (Sinnett et al., 2001). The vertical jump test has been applied in numerous sporting codes (Baker, 1996) although within rugby league it has been unable to discriminate between backs and forwards (Gabbett, 2000, Gabbett,

2002). The inability to differentiate between back and forwards may not be a result of the simplistic nature of the vertical jump test but rather the fact that all rugby players display a high level of lower body strength.

The application of field based tests has allowed for the relatively easy acquisition of strength and aerobic capacity of athletes in their preferred environments. While these tests do add to the understanding of sports performance they cannot accurately mimic the effects of a match. Furthermore a match cannot be used as a repeatable intervention as there are unknown and unrepeatable variables between matches. Consequently researchers have developed match simulations in an attempt to standardise the characteristics of a match.

1.4.9 Match simulations

The use of match simulations to test skills in a more controlled environment is an alternative to using unknown parameters (quality and intensity of the opposition) to assess individual or team performance (Reilly, 2001). Many investigators have used match simulation of various sports (reviewed by Currell and Jeukendrup, 2008) including soccer (Williams et al., 2010; Azidin et al., 2015); basketball (Moreira et al., 2012); and rugby (Higgins et al., 2013). The use of a simulation allows for all the participants to cover a similar distance and perform a similar quantity of tasks. Furthermore the tasks can be assessed without external factors such as the opposition and match pressure. While these two factors may have a considerable influence on the overall match performance they are inherently difficult, if even possible, to recreate. One pertinent example of a match simulation that specifically applies to rugby was developed by Roberts et al. (2010). The Bath University Rugby Shuttle Test (BURST) (Roberts et al., 2010), an 80-minute match simulation model of rugby, is used in this thesis (Chapter 8). The simulation requires players to run at various speeds, and perform tasks

specific to an 80-minute rugby union game: rucks, mauls and scrums. The simulated rugby match protocol lasting a total of 80 minutes is divided into 16 cycles, each of which has five task units. The tasks performed in each cycle were simulated scrummaging, mauling and rucking. A scrum is simulated through a weighted individual scrum machine, which is driven backwards by the player for 7 seconds, over a distance of 1.5m. Rucks are simulated through the tackling and carrying of a 20kg tackle bag for 3.5 seconds over 5m. Lastly the maul is simulated by a contest for the ball over 5 seconds. The participant that started with possession of the ball is required to maintain possession, while the attacker will attempt to wrestle for the ball. After the completion of eight cycles the participants are given a half-time break of 10 minutes. The comparison between the BURST and a match revealed similarities in the distance covered (7078m in BURST compared with 6418 ± 862m in the match), velocity bands of locomotion and number of static exertions were in agreement with match data (Roberts et al., 2010). The simulation may however overestimate the number of scrums (32), rucks (64) and mauls (16) that an individual player may partake in. The BURST was compared to a single professional club game, which does not represent the best comparison of general rugby games. Furthermore the BURST is a simulation exclusively for the forwards, based on the movements and tasks performed during the simulation (Roberts et al., 2010).

1.4.10 Application of science to the coach and athlete

A major component of the success of a team or individual is through the application of science to the coaches or sportsmen. An online survey of coaches from a variety of sporting disciplines and levels revealed that they prefer to gather their new information through informal meetings rather than formal education programs (Stoszkowski and Collins, 2016). The main concern with this method of information transfer is the reliability of the sources.

Incorrect application of information could have detrimental effects to a team's performance. Another aspect of performance that relates to the coaches is the application of feedback. Liebermann et al. (2002) summarised that giving individuals feedback regarding movement patterns can result in alteration in the posture however, they stressed that individuals must be aware of the performance implications and the correct postures. One possible way to give feedback is through the use of technology. The most common of these methods is the use of video based technology (Liebermann et al. 2002). Video-based reporting of tactical and performance aspects is vital to the success of a team. The video feedback allows for individuals within the team to identify and correct, if necessary, any specific tasks requiring attention (Hohmann et al., 2016). Moreover the current availability of smart phones and the ease of access to applications have allowed for rapid feedback avenues. There are applications that can record and measure kinematic variables (for example Dartfish Express and MySprintApp), with acceptable to high degrees of accuracy.

While these techniques are readily available and may prove to be beneficial to the athlete and coaches, there still exits a major lack of 'buy-in' from the relevant parties. Coaches and athletes to a large extend remain sceptical of procedures or techniques that *may* improve performance. Therefore there still exists a need for a sports scientist to decipher, apply and where necessary instigate research within the team environment.

In the preceding section the various methods of assessing sports performance have been identified. The areas of assessment include: technical; morphological; physiological; and psychological variables which when individually optimised may improve individual performance. Specific to rugby the previous section has highlighted how development of efficient physiological systems and improvements to morphology can improve individual

rugby performance. Psychologically, while a rugby match may not improve mood states, strategies to reduce the loss of positive mood states and reduce the fluctuations of mood states may be required to improve performance. A brief summary of technical sports performance was stated specifically focusing on kinematic evaluations. The following section will identify and discuss technical performance specific to rugby tasks. In the current thesis I have selected to use performance indices to establish a quantifiable measure of individual contributions to team performance. While the selected indices may not independently reflect team performance, their contributions to the team performance are paramount to the success of a team. These are: the ability of all players to accurately execute passes; ability of specialised kicking players to achieve the necessary distance and accuracy; and the ability of scrummaging players to produce compressive scrummaging forces as true reflections of individual performance indices. Furthermore, their summation may, to an extent barring the interplay within the team, reflect team performance.

1.5 Player's proficiency in performing rugby specific tasks

As previously shown, rugby performance can be attributed to the technical ability of an individual performing a task (Lees, 2002). Therefore identifying and assessing the technical ability of an individual's performance of a task could possibly lead to more efficient application of the skill and indirectly to improved team performance. This detailed section will focus on the fundamental tasks of rugby.

1.5.1 Performance of rugby specific tasks

The rugby specific performance tasks which are the major focus of the chapters within this thesis are: passing accuracy, kicking distance and accuracy and scrummaging force generation. These are related to the following six specific team tasks, outlined by Jones et al.

(2008): passing accuracy is reflected by ‘seven or more phases’ as well as ‘passes made’; kicking relates to three different identified tasks (open-play and restart kick success and goal kick success); and scrummaging force generation relates to the scrum tasks (scrum success and scrum gain-line made).

The ability of individuals to perform these rugby specific tasks, namely passing, kicking and scrummaging, will be discussed in the sections to follow. The main focus will be on: determination and quantification of performance outcomes which have been used to measure the degree of success in each task; studies quantifying the skill (kinematics) considered to be important for the identified tasks; and any other contributors that affects their specific performance outcomes. Although not a focus of this thesis a number of other rugby specific tasks have been studied and undoubtedly play a role in the success of a rugby team. In particular tackling, lineouts, mauls and rucks have been reported in the literature as game defining features. Therefore, included in this literature review is a brief account of the current research into tackling, lineouts, mauls and rucks.

1.5.2 Passing: the fundamental skill linking individuals in a team

The gain in field position and physical momentum while the ball carrying player is running is a major component to the success of a rugby team (Higham et al., 2014). Preventing this happening however, is a major task of the opposing team whose major tool of disruption of such momentum is the tackle. In order to avoid the tackles of a defending team the rules of all rugby codes allow for a ball to be passed between players and therefore allow for continued progression. Passes must only occur in a backwards direction, with reference to the attacking direction of the player passing the ball. Even though all rugby players are required to be proficient at passing the ball (unlike specialist areas distinct to rugby such as the scrum and

lineout), variation in passing ability among playing positions has been reported (Gabbett, Kelly & Pezet, 2008).

Passing in rugby is a dual handed task; however unlike other dual handed sports (for example golf, cricket, baseball and racquet sports) there are no additional segments to the kinetic chain. The hands are positioned at opposite ends of the ball length wise with the back hand providing the power and the spin (Tomlinson et al., 2009) and the front hand providing stability. The back hand will push through with the palm, and as the motion continues the fingers will sequentially leave the ball imparting spin along the longitudinal axis of the ball (Tomlinson et al., 2009). For the purposes of this review running and ground passes will be treated as distinctly different actions. The running pass is comparably more dynamic than the ground pass. Additionally the running pass is a skill required by all players regardless of their playing position, whereas the ground pass may be more positional specific. The differences between the two passing types are highlighted below.

The running pass is carried out as follows: firstly the individual identifies their target. This is followed by planting the lead leg, which is the opposite leg to the direction of the pass. This motion will cause the pelvic girdle to be orientated towards the target. During this sequence the shoulder girdle will be actively rotated towards the target and the arms will swing towards the direction of the target. The arms will be extended and will require the optimal proximal to distal segment sequencing. The running pass is performed when a team has ball possession and is required to move the ball between players. All of the players on the field are required to have an adept level of running pass proficiency.

Another passing type in rugby is the pass from the ground. When a scrum or breakdown occurs the ball is placed on the ground where the arriving player will attempt to distribute the ball to another advancing player. The ground pass is made from a comparatively static

position, compared to the running pass. The ground pass is a more positional specific task compared to the running pass, as the ground pass is usually performed exclusively by the scrum-half. However if the scrum-half is unable to distribute the ball from a breakdown, the first arriving player able to access the ball will distribute it.

The ground pass was described by Frenzilli and Leighton (1989) and assigned four stages: contact; extension; passing; and follow-through. Contact was presumed to be the initial point of contact between the player and the ball. The player would normal be in a crouched position to gather the ball from the ground. The extension phase was considered to be when the player underwent limb segment extensions during which the player may choose to step with their lead leg towards the intended target. The passing phase is described as the phase when the ball is released from the hands. The player will optimise their limb segments in a proximal to distal fashion attempting to pass the ball the required distance. The follow-through was described as the phase that dissipated the excess energy of the arms following the release of the ball. The major contributors to the ball velocity of the ground pass are the maximal velocities of the shoulders adductions and flexions, which have been shown to coincide with ball release (Sayers and Ballon, 2011). Thus reinforcing the importance of the kinetic chain and segmental sequencing.

1.5.2.1 Quantifying passing proficiency

Passing performance has two distinct physical properties which both may determine passing success, namely: ball movement dynamics and passing accuracy. The following section will summarise the current literature surrounding the pass in rugby with specific focus on the performance outcomes, measurement of pass accuracy, and the variables that contribute to passing success.

Ball movement dynamics (ball velocity, spin and distance travelled)

Frenzilli and Leighton (1989) ascribed three descriptors of passing performance, namely: velocity, distance and accuracy. The first two parameters are mutual as the velocity of the pass is dependent on the distance that it has to travel (Worsfold and Page, 2014). While the third component, accuracy, is measured independently from distance and velocity, it has been shown that accuracy decreases over increasing pass distance (Worsfold and Page 2014). The potential relationship between passing accuracy and ball velocity is yet to be defined.

Passing further distances allows players to occupy a greater area of the field and still potentially execute a pass. However an extended duration of the ball flight may be detrimental to the passing team. The ball flight time allows the defenders to advance towards their opposition, thus reducing the space for attacking plays to occur.

The most widely used passing method is the spin pass, in which the player will impart spin onto the ball which assists in the stability of the ball during flight. The amount of spin imparted to the ball is dependent on the level of friction between the hand and the ball but is not affected by moisture on the ball (Tomlinson et al., 2009). The number of ball rotations increases with increasing distance, which endorses the stability of the spin pass (Worsfold and Page 2014). However the spin imparted onto the ball may reduce the accuracy of the pass, as the ball may drift toward the direction of the spin. The drift of the ball is reported to dependent on the flight path angle, pitch and velocity vector of the ball (Seo et al., 2006). In terms of the spin pass, it is expected that faster passes (those with a greater velocity vector) will drift more towards the direction of the spin the further the pass distance. Hooper et al., (2008) showed how training regardless of the ball mass could improve maximal pass distance, pass velocity and increase the ball spin. The increased spin was only observed to the non-dominant direction (Hooper et al., 2008). Their results indicate that the practicing of

passing may help the overall action and improve performance rather than the use of balls of different masses. It has been previously hypothesised that training with equipment of increased mass may improve the performance of the task (Hooper et al., 2008).

Pass accuracy determination

There have been multiple assessments of passing accuracy using various different limits for determining an accurate pass (Pienaar et al., 1998; Stuart et al., 2005; Hooper et al., 2008; Spamer et al., 2009; Tomlinson et al., 2009; Assi and Bottoms, 2014; Worsfold and Page, 2014). However the quantification of pass accuracy has historically been crude (usually a binomial distribution of whether or not a player was able to hit targets of different sizes) and idealistic (based on theoretical notions of what constitutes an accurate pass). A brief summary of the dimensions, heights above the ground and target distance from previous literature are listed in Table 1.1.

The lack of continuity of the definition of an appropriate and relevant passing target size (as well as the variations in distances used between the target and players) confounds the interpretation of these studies and their conclusions regarding factors related to passing accuracy. Arguably one of the most representative targets was presented by Worsfold and Page (2014). The lower limit corresponds to the height of the iliac crests of the average rugby player, and the upper limit to the height of the average rugby player. The width was defined by the recommendation from Greenwood (1997) that passes should be 0.91m (3 feet) ahead of the receiving player. Sayers (2011) reported in his analysis of the line-out throw that accuracy should be defined by the catchability of the throw. For that reason, he developed an accuracy rating scale based on the movement of the intended receiver relative to the position of the ball. Similarly Dichiera et al. (2006) assessed the accuracy of the Australian Football punt based on the catchability of the ball. Their target was a life-size cut out of a player, with

a target (24cm diameter) centred on the chest. Kicks were considered accurate if they made contact with the target or if they missed the target at the correct vertical height, within the left and right limits. These left and right limits were presumably the extent to which a player can reach for the ball.

Table 1.1: The differences in the dimensions and positions of passing accuracy targets.

Investigating study	Target dimensions (height x width) (m)	Height of target from the ground (m)	Distance of passes (m)
Stuart et al., (2005)	1x1	1.5	4
Hooper et al., (2008)	NS	unreported average chest height of the participants	7, 10
Pienaar et al., (1998)*†	0.6-1.8 (circular diameter)	0.5	4, 7
Tomlinson et al. (2009)	0.2x0.2	average relative chest height (deduced from their figure 3)	10
Assi and Bottoms (2014)	0.75 (circular diameter)	unreported participants' average chest height	5
Worsfold and Page (2014)	0.91x0.85	0.92	4, 8, 12

NS Not Specified within the text

* Target consisted of three circular targets: outermost diameter was 180 cm with middle and inner targets 120 and 60 cm respectively. Points were awarded based on the striking of the target inner: 3; middle: 2; outer: 1.

† target has been used in subsequent studies by Spamer and colleagues (2009)

The idea of rating the accuracy could be applied to the pass. An accurate pass should not affect the running velocity of the intended receiver. Therefore the aim of the intended pass should be slightly ahead of the receiver (Gabbett, Kelly and Pezet, 2008) and at a height that does not require the receiver to bow, jump or maximally reach for the ball. Passing towards this virtual target allows for the receiving player to maintain or increase their running velocity

while attempting to catch the ball. Therefore passing accuracy should incorporate the limits of the receiving player so that running velocity can be maintained. Passing accuracy should be defined by the limits of comfortable catching heights of the players, without impeding running velocity.

1.5.2.2 Known determinants of passing accuracy

Despite the inconsistency in the definition and quantification of passing accuracy, a number of factors have been identified as being important as determinants of an accurate pass. These factors are: the influence of hand dominance, the role of different kinematic strategies, and the role of running speed. In the subsections that follow, each of these determinants of passing accuracy is discussed.

Hand dominance and its influence on passing

Current research has highlighted the effect of hand dominance on the rugby pass, both maximal distance (Pavely et al. 2009) and over various set distances (Sayers and Ballon, 2011; Worsfold and Page, 2014). Evidence suggests that passes with the dominant hand or preferred side are more likely to be legal, achieve maximal pass distance (Pavely et al., 2009) and greater velocities (Sayers and Ballon, 2011) than those made using the non-dominant hand. Worsfold and Page, (2014) reported higher ball rotations with passes executed with the non-dominant hand. Consequently the over rotation of the ball may result in the pass being less accurate. The two discrepancies, pass velocity and over rotation of the ball, may be an effect of reduced intersegmental control on the non-dominant side. The resulting kinematic event of the pass must require an adept level of muscular control, specifically the temporal-spatial control of segments. From these studies it can be seen that a preference to a particular side is present in players. The passing-side preference can potentially result in poor execution

of the pass. Pavely et al. (2009) further reported for a single experienced international player that different segmental patterns are used for the preferred and non-preferred sides. This shows that regardless of the playing level of the individual that a preference to a particular side is present.

Passing movement strategies

The running pass is the most effective way to maintain possession while improving the team's field territory. The execution of a running pass should occur at maximal running velocity and result in an accurate pass. However it would seem that the passing sequence might be affected by the speed of locomotion, the stage of stride in which passing occurs and a number of different (more subtle) variations in movement strategy. Each of these passing movement strategies is discussed below.

Running speed

Running speed is impacted by the position that the rugby ball is carried in while running. Running speed has been shown to be reduced when the ball is carried in both hands compared to a single side (Grant et al., 2003; Walsh et al., 2007). This running speed difference was independent of the playing experience of the rugby player (Walsh et al., 2007). Furthermore carrying the ball in both hands was shown to reduce players' abilities to perform agility tests (Meir et al., 2014). In all cases the underlying mechanism for the reduction in running performance is attributed to the restriction of the upper body segments thereby reducing their ability to counter the momentum of the lower body (Ropret et al., 1998; Grant et al., 2003; Walsh et al., 2007; Meir et al., 2014; Barr et al., 2015). In an elite playing group the differences between ball carrying techniques did not reduce sprint velocities however there were increased sprint velocities were exhibited between backs and forwards (Barr et al., 2015). This difference in in sprint velocity may not be attributable to the effect of ball

carrying, but may be the known inherent difference of running velocity between forwards and backs (Duthie et al., 2006; Gabbett Kelly, Pezet, 2008; Jones et al., 2015). Therefore previous results of running velocity with ball possession may not apply to elite players, as it does in amateur players. The lack of difference in the elite player may indicate their trained ability to maintain running velocity with ball possession.

Step sequence

The kinematics of the running pass may be affected by the changes in the gait cycle resulting from the increased speed of locomotion, specifically with respect to the rotation of the pelvis. The pelvis can either be internally or externally rotated depending on the speed at which a person is running (Schache et al., 1999). Normally during running the pelvis will undergo external rotation towards the side of the support limb. By the time the foot makes contact with the ground the pelvis will be slightly rotated towards the stance side. Maximal external rotation of the pelvis is normally achieved mid stance (Schache et al., 1999; Schache et al., 2002). Because pelvis rotation may influence the mechanics of the passing action it may potentially change variables which could affect pass accuracy. To my knowledge, there have been no studies that have assessed the step sequence of passing in rugby.

Passing strategies

The kinematic strategies used to perform the running pass were investigated by Worsfold and Page (2014). They showed that the technique of the players can affect pass velocity and accuracy. Players were classified based on whether they lowered or raised their whole body centre of mass (CoM) position prior to the pass. Players who elevated their CoM position prior to ball release performed more accurate passes with higher velocities, regardless of the direction of the pass (Worsfold and Page, 2014). Furthermore players used the body drop technique more frequently when performing passes to the non-dominant side (Worsfold and

Page, 2014). This would suggest that players utilise different whole-body passing strategies depending on pass distance and the direction of the intended pass.

Anecdotally there are two commonly used methods to coach passing. The first relies on larger rotation of the shoulders, and the second method relies on the extension of the arms and less on torso rotations. These two strategies can be seen in the study by Pavely et al. (2009) in the assessment of an experienced international rugby player. The pass to the non-dominant side, compared to the dominant side, exhibits less torso rotation and greater abduction of the arms- specifically the pushing arm was further away from the torso (Pavely et al. (2009) Figure 1. page 138). This technical discrepancy between passes towards the dominant and non-dominant sides may have implications regarding performance, specifically the pass distance and accuracy.

One particular passing strategy a player may select is the draw-and-pass. The draw-and-pass is described as follows: Firstly, the ball carrier must attempt to pass the ball when their body is positioned on the inside shoulder of the defender. The ball carrier must take a small step away from the defender (this will draw the defender towards the ball carrier) and maintain their body position square with defender. The ball carrier will attempt to pass the ball in the opposite direction to the leading (planted) leg. The player passing the ball must correctly identify when to pass and when to run into the space. In a two-on-one situation the defender may want to defend the ball carrier or the player that will likely receive the ball. The ball carrier must maintain an appropriate distance from the defender as to prevent the possibility of interception of the pass. The strategy allows for the creation of space for the receiving player, as the defender will attempt to stop the ball carrier (tackle the ball carrier prior to passing). This strategy is successful if the ball carrier can cause the defender to move thereby creating a gap (Gabbett, Wake and Abernathy 2011). Such beneficial strategies are likely trained into players and individual variations of this technique are developed based on the

players' physical capabilities. This method is widely used in rugby league (Gabbett, Wake and Abernathy 2011). Gabbett and Abernathy (2012) showed that nearly half of all tries scored in a season of rugby league were attributable to players using the draw-and-pass technique. Due to the nature of rugby union the draw-and-pass is less crucial to the gameplay and has subsequently not been reported in the literature. There is however no reason that a rugby union player would not perform such a strategy. In fact, match analysis may show, in the sequence of passes leading up to a try, that the majority of passes are performed using the draw-and-pass technique.

Another potential strategy may be related to the velocity of the passing player. Players may choose to run slightly slower than maximal velocity to allow for the effective execution of technical tasks such as kicking and passing (Walsh et al., 2007, Barr et al., 2015). A player attempting to pass may, in the steps leading up to the pass, reduce their velocity in order to perform a more accurate pass. However the reduction in the running velocity may not be a consciously chosen strategy and may be an effect of carrying the ball.

The current section has highlighted that individuals may use different strategies to perform the pass in rugby. Further the importance of accuracy and specifically catchability of the pass was identified as a vital performance outcome. Accuracy and catchability of the pass ensure that the team are able to gain territory. Another means of gaining territory is using the kick.

1.5.3 Kicking: a device for the attainment of points and field territory

In rugby, kicking can be used to gain territorial advantage over the opposition and is also a key strategy available to a team to score points. Despite the territorial advantages of kicking, it should be noted that using kicking as a territorial strategy often trades-off such potential advantage with the calculated loss of ball possession by the kicking team.

There are multiple types of kicking styles used in rugby and all are usually performed by the best kickers on a team, theoretically from any position, but most commonly back line players. The following section will primarily describe the place kick, drawing from literature surrounding place kicking performance, but also relating the findings from all forms of football kicking in order to more widely describe the current state of knowledge surrounding the science of kicking. Supporting this, Ball and colleagues (2013) reported that the foot position exhibited during the soccer instep kick is not dissimilar to that exhibited in the rugby kick.

1.5.3.1 Kicking performance outcomes

Quarrie & Hopkins (2015) reported that an average of 45% of the points during a rugby game resulted from successful place kicks. The kicker must have the ability to kick the ball long distances as well as be accurate enough to get the ball through the up-rights, spaced 5.6m apart. Therefore a successful rugby place kick requires accuracy and sufficient velocity to reach the necessary distance. Nel (2013) further emphasized the importance of both kick accuracy and distance by establishing a success probability equation for the place kick in rugby, which included the altitude of the venue, angle of the kick, and the distance of the kick.

In rugby, kickers have a total of 60 seconds from when the tee arrives on the field to when the kick must be performed. During this minute the kicker will align the ball with the intended target and the kicker will follow an individual routine. Jackson (2003) analysed the kicking routines from the 1999 Rugby World Cup and found that the preparation time of important kicks (those in which teams were divided by a small margin) favoured longer concentration time over physical preparation. However there were no significant differences between the

best and worst kicking performers regarding their total routine time, consistency or rhythmicity (Jackson 2003).

Kicking Accuracy

The targets for all points based kicks in rugby are the posts. Any kick attempt is required to pass within the 5.6m width of the uprights and pass over the 3 metre height of the crossbar. The target may appear to be narrower depending on the position of the attempted kick. That is place kicks attempted from the touch-lines along the length of the field would have a slighter angle than an attempted kick from directly in-front of the posts.

Kicking difficulty can be determined using the position of the kick attempt along an arc length to the posts (Jackson and Baker, 2001). Using this method, it can be observed that kicking difficult follows an arc. As the arc is shifted away from the centre of the posts and as the length increases, the kick becomes more difficult. The accuracy of the kick may be dependent on the range of motion of the kinetic links during the kicking sequence (Lees and Nolan, 1998). The kinematics of the kicking sequence will be discussed in the proceeding sections.

Measuring accuracy can prove to be a difficult task as the angle of the kick towards the target may not favour a straight kick. If the target angle is oblique the kicker may choose to shape the kick in between the posts. This can be done by imparting spin onto the ball.

Imparting spin: the foot-ball interactions

The interaction between the foot and ball can have significant effects on the resulting trajectory of the ball (Asai et al., 2002). In soccer the position of the foot strike on the ball will impart spin, depending on the distance from the centre of the ball. The closer to the centre of mass of the ball that the resultant velocity vector (arising from the foot centre of

mass) strikes will result in less spin and a higher resultant ball velocity and therefore distance (Asai et al., 2002).

A specialised ball able to directly measure the spin of the ball was manufactured that had gyroscopes within the body of the ball (Fuss et al., 2013). The application of this spin quantifying ball showed that rugby punt kicks exhibited more spin than Australian Football punt kicks. Spin (along the longitudinal axis) stabilised the ball in flight. There was no relationship between the amount of spin and accuracy (Fuss et al., 2013). In the place kick it is not common for the ball to experience a considerable amount of spin along the longitudinal axis of the ball. The ball will predominantly tumble end over end (Linthorne and Stokes, 2015). While the tumbling action may not be the best aerodynamic option, it is near impossible to impart longitudinal spin onto the rugby ball in the majority of kicks. Additionally a tumbling action may be preferred by the kicking team as the aerodynamic instability of the ball may result in the retention of possession.

The trade-off between kicking velocity and accuracy

The trade-off between the projectile's velocity and accuracy has been shown in various sporting disciplines (Sachlikidis & Salter, 2007; García et al., 2013) and in the soccer kick (Teixeira, 1999; Asai et al., 2002; Kallis & Katis, 2007). Initially Teixeira (1999) showed how higher ball velocities were achieved when participants simply kicked towards a target compared to when they were instructed to hit specific targets. The potential trade-off between distance and accuracy is due to the position that the foot strikes the ball (Asai et al., 2002). This in the context of rugby is compound further by the shape of the ball. The soccer ball is spherical thus presenting with a uniform centre of mass position. The rugby ball however is less uniform and the ball centre of mass position relative to the foot can vary greatly, depending on its orientation. Indeed the trade-off between distance and accuracy has been

reported in the rugby place kick (Bezodis et al., 2007; Padulo et al, 2013; Sinclair et al., 2014a).

Ball velocity and travel distance

The major contribution of points from the place kick necessitates that kicks should be successful from the majority of attempted kicks. While the bulk of kicks are comfortably within the limits of most players, the limits of kicking distance are being challenged by most modern rugby kickers.

Maximal kicking distance is rarely the focus of rugby kicking studies, which may reflect a preferential focus on kicking accuracy. The lack of emphasis may reflect the changing of rugby gameplay, or that kickers will only agree to a kick what is within their limits (within 40m from the posts). Padulo et al., (2013) assessed the effects of different approaches to the kicking tee and the resulting ball velocity from a distance of 40m and found that the resultant ball velocity was dependent on the amount and angle of the approach steps. Sinclair (2014a) used velocity equations to determine that the distance of their participants' kicks would have been in excess of 60m. Although this calculation of eventual kick distance is contentious as the effects of environmental constraints were not included. Additionally the ball trajectory and aerodynamic nature of the ball could influence the overall kick distance. Linthorne and Stokes (2015) mention that the tumbling action of the ball in flight could theoretically reduce the maximal distance of the kick by up to 10m. Although the exact distance would remain unknown, when applying equations, it would seem that maximal place kick distances are closer to 50m (Holmes, 2006). The resulting kick distance can be related to the projection angle and projection velocity of the kick (Linthorne and Stokes, 2015). The projection angle and velocity may be an individually developed skill. This may relate to an intrinsic limit of individual kicking distance. It is important to note that the kick, in order to be considered

successful has to pass over the crossbar (3 metre in height). Therefore the trajectory of the kick in the final stages has to be above this limiting height of 3m and not at the level of the ground. Furthermore the kick trajectory may not be ballistic in the sense that it is symmetrical about the horizontal axis (towards the intended target).

The kick distance is the result of the generation of maximal energy being transferred via the kinetic chain to the ball. To impart maximal velocity to the ball the energy generated should occur in a proximal-distal fashion (Naito et al., 2010; Shan & Westerhoff, 2005; Sinclair et al., 2014a, b; Urbin et al., 2011; Zhang et al., 2012).

1.5.3.2 Kicking kinematics

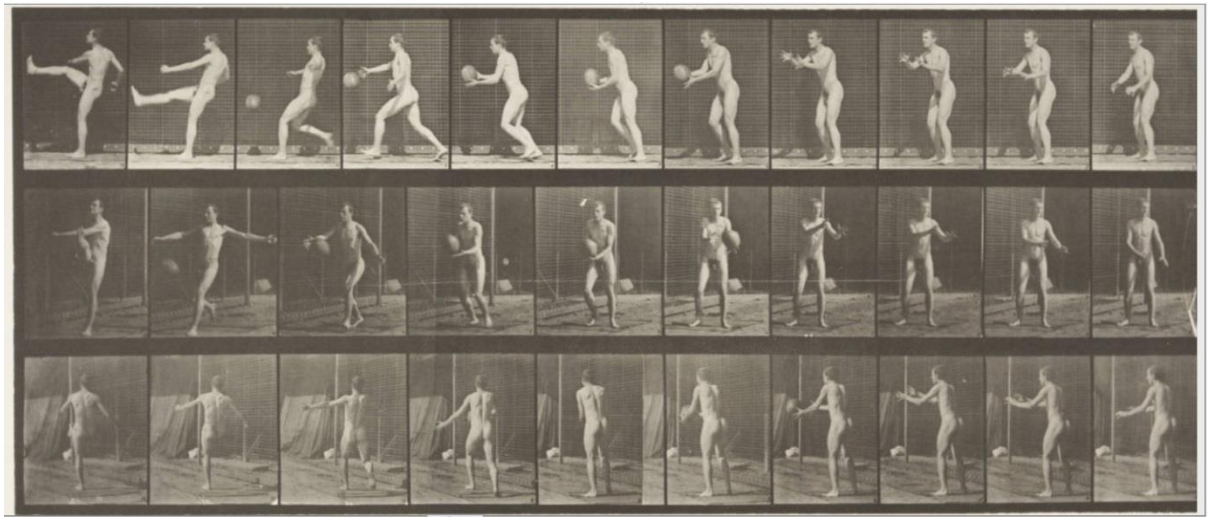


Figure 1.5 The sequential motion of a man kicking a ball out-of-hand. (Muybridge, 1957).

Perhaps the earliest study of kicking technique was by Muybridge in 1887 (Figure 1.5) in his collection of images entitled ‘Animal Locomotion’. It is worth noting that these plates depicting the kicking action were developed a mere 24 years following the separation of football into soccer and rugby. Kicking is a complex biomechanical action that requires the controlled and intricate coordination between the segments of the torso and arms (in the case

of the drop punt) as well as the lower body, both temporally and spatially (Urbin et al., 2011; Bezodis et al., 2007; Kallis & Katis, 2007; Manolopoulos et al., 2006; Naito et al., 2010; Shan & Westerhoff, 2005; Urbin et al., 2011). To describe the sequence of the kinetic chain the proceeding sections will discuss the kicking kinematics from the ball approach to the determinants of ball velocity. The kinematics of the kicking action have been studied by many researchers specifically in soccer (reviewed by Lees, Asai, Andersen, Nunome & Sterzing, 2010) and Australian football (Hart et al., 2014). Previous researchers that have examined the place kick in rugby have focused on kicking models and kicking performance (Bezodis et al., 2007, Ball et al., 2013, Sinclair et al., 2014a). The success of a place kick is currently thought to be reliant on both biomechanical skill, such as the optimization of the kinetic chain (Bezodis et al.,2007; Zhang et al., 2012), and on physiological factors, such as lower body strength (Zhang et al., 2012). Throughout the kinematic description of the kick, performance parameters that contribute to either ball velocity or kicking accuracy will be identified.

Approach angle and velocity

Prior to kicking the ball, a player will normally take a few steps from a set position to strike the ball (Jackson, 2003). This run-up or approach will allow the kicker to orientate themselves in the preferred position to impart maximal velocity onto the ball. Lees and colleagues (2010) mentioned the positive relationship between greater length of the last stride and greater forward rotation of the pelvis, which in turn can result in more energy generated during the approach. While this relationship is a contributing factor it is likely that the efficient transfer of energy between segments is more important for achieving distance with the kick (Kellis, Katis & Vrabas, 2006).

Padulo et al. (2013) assessed the effects of different approach styles in the rugby place kick. They reported that longer run-ups resulted in increased ball velocity but decreased their success rate (Padulo et al., 2013). There must be an individual preference in the procedure that individuals choose when approaching the ball during their run-up, both in velocity and approach angle.

Stance leg plant and foot placement position

Following the approach, the kicker plants their non-kicking leg (stance leg) firmly onto the turf which reduces the kicker's whole body velocity, and also assists in creating a pivot around which the energy generated during the approach can be transferred.

While ball velocity has been shown to be related to various parameters in the kinetic chain (Sinclair et al., 2014a; Kellis and Katis 2007), no changes to ball velocity have been reported for stance foot positions in rugby players (Baktash et al., 2009). This is likely due to the similar positions of foot placements across the spectrum as even though place kickers exhibit a range in their approach angles and velocities, when they are required to place their stance leg prior to kicking they display very little variation (Cockcroft & van den Heever, 2016). However, knee velocity and knee moments changed slightly when the planted foot position was altered (Baktash et al., 2009). The positions of the plant foot in this study were predetermined however and not as a result of individual variation. It would therefore seem likely that the alterations to the knee parameters were a result of the minor change in the kinetic chain. Of particular interest are the playing levels and the sample sizes of these two studies. Both studies investigated high playing level individuals (international) however they both reported limited sample sizes (n=3 Baktash et al., 2009 and n=15 Cockcroft & van den Heever, 2016). The playing level may compound the lack of results, as higher playing level individuals may display less variation in their techniques.

Upper-body contributions

Throughout the kicking sequence the upper-body is in motion. The next two sections investigate the contribution of the upper-body, specifically the torso and the arms, to kicking success.

The initiation of the kicking sequence has been suggested to begin with rotation occurring at the pelvis (Kallis & Katis, 2007; Sinclair et al., 2014b; Zhang et al., 2012). However, Naito and colleagues (2010) showed in the soccer instep how larger trunk rotations could lead to higher knee extension velocities and subsequently larger ball velocities.

Shan & Westerhoff (2005) describe the sequence of a dynamic tension arc, whereby the potential to generate energy was initiated when the distance was maximized and actively released during the kicking sequence (Shan & Westerhoff, 2005). To briefly describe the sequence: The kicking side hip exhibits overextension and trunk rotation is orientated towards the non-kicking side, with the non-kicking side shoulder extended and in an abduction position. Following through the sequence the proximal to distal chain of the kicking leg is controlled; the trunk flexes and is rotated towards the kicking side; while the non-kicking side shoulder is adducted and flexed (Shan & Westerhoff, 2005). This description demonstrates that the kicking action is not limited to the kinematics of the legs but rather involves the entire body. Furthermore there appears to be differences in the usage of this tension arc between players of different skill levels. Shan & Westerhoff (2005) showed that more skilled players make better use of their trunks when kicking. Skilled players displayed a smaller distance between their non-kicking side shoulder and their kicking side hip at the completion of the tension arc (Shan & Westerhoff, 2005).

More recently Fullenkamp et al. (2015) showed the importance of the trunk rotation in attaining ball velocity in the soccer kick. Their findings show that practiced kickers exhibit a

higher axial trunk range of motion and greater peak trunk rotation velocity compared with their novice counterparts (Fullenkamp et al., 2015). Additionally they reported a moderate relationship between the velocities of the trunk rotation and the resulting ball velocity (Fullenkamp et al., 2015). These findings shift the initiation of the kinetic sequence further up the chain to the level of the torso. While the kinetic chain may extend to the upper body their still needs to be optimal energy transfer between the segments. This requires the time to peak velocity in the segments to be perfectly timed. The peak rotation of the pelvis has been reported to have a relationship with the post ball strike ball velocity (Fullenkamp et al., 2015). It must be stressed that the results from both the Shan & Westerhoff (2005) and Fullenkamp et al. (2015) studies indicated differences in the upper bodies between skilled and unskilled kickers. Therefore any inferences made regarding their potential contributions to the kicking performance must be made with caution. However there must exist a continuum on which the upper body motion and their effects on kicking performance lie.

In the tension arc description of the kick, it was observed that the arms play a major role during the kicking sequence (Shan & Westerhoff, 2005). Bezodis et al. (2007) investigated the contributions of the non-kicking side arm within rugby place kicking technique. They reported that more accurate kickers exhibited greater angular momentum of the non-kicking side arm about the anterior-posterior axis, which changes the degree of the lateral bend of the torso at ball-contact (Bezodis et al., 2007). Additionally accurate kickers displayed larger angular momentum values of the non-kicking side arm about the global longitudinal axis. This was reported to oppose the kicking leg angular momentum about the same axis. Furthermore the angular momentum of the non-kicking side arm increased as the kick distance increased. These results indicate that the momentum of the non-kicking side arm about the longitudinal axis may contribute to the accuracy in the rugby place kick (Bezodis et

al., 2007). It is likely that the non-kicking side arm is used to counteract the momentum generated by the kicking leg through the sequence.

The study by Bezodis et al. (2007) indicates that the arms act as a method to stabiles the body during the kicking sequence and therefore assist in the dynamic control of balance. A refined level of dynamic balance is required during the kicking sequence. Indeed kicking accuracy, but not kicking velocity, has been significantly related to single leg balance (Chew-Bullock et al., 2012). Furthermore the relationship with kick accuracy was more highly correlated with the balance in the non-dominant kicking leg (that is the stance leg) than the dominant kicking leg. The stronger relationship reported in the Chew-Bullock et al. (2012) study while correlational in nature, does indicate the importance of the single leg balance of the stance leg. The stance leg of proficient kickers should have the ability to maintain balance of the whole body during dynamic tasks such as kicking, where the position and velocity of the kicking leg is actively altering the whole body centre of mass.

Leg segments

The segments of the legs are the primary determinants for kicking ability since it is their momentum which is directly transferred to the ball. While the approach, foot plant position relative to the ball, and upper-body motions may contribute to kicking performance, maximal ball velocity may be as a result of the energy generated by leg segments that ultimately determines kicking performance. The effects of the three segments (thigh, shank and foot) may independently affect the kick velocity and accuracy. Indeed the velocities of the thigh shank and foot have all been implicated in the generation of maximal ball velocity (Kellis and Katis 2007). Similarly, Zhang et al. (2012) reported that the biggest contributor to ball velocity in the rugby place kick was the extension of the knee followed by the flexion of the hip.

While the independent action of the leg segments have been associated with ball velocity, the additive effect of these segmental velocities when maximized in a proximal to distal fashion should give a better representation of ball velocity (Nunome et al., 2006). Kellis and Katis (2007) summarised that angular velocity is maximised by the thigh segment, which is imparted to the shank segment, further increasing the angular velocity and finally transferred to the foot, which imparts a further angular velocity to the ball. Baktash et al., (2009) showed how efficient transfer of energy between the segments of the kinetic chain will usually result in greater kick distances being achieved. From these statements it is noted that the angular velocities of the joints are likely to determine not only the velocity of the ball, but the velocity of the proceeding segment.

The kinetic chain needs to exhibit an efficient transfer of energy between the segments. For example, the deceleration of the thigh segment has been shown to result in increased shank acceleration (Nunome et al., 2007; Naito et al., 2012). It is possible to optimise the interactions between the two segments (the joints and their angular velocities). Sinclair et al. (2014b) showed that peak knee extension velocity was related to ball velocity in the soccer instep kick (R^2=0.39) and a similar relationship in the rugby place kick (R^2= 0.48) (Sinclair et al., 2014a) however, their results show that a larger amount of unexplained variance exists. A more complete description of the relationship in the kicking sequence is required, regardless of the sporting code.

The drop kick

A brief description of the drop kick was given in section 1.3.2.2. As noted within this section the drop kick is a method to restart the game and can be used to accrue points during open play as a field goal. One assumption is that the kinematic predictors of the place kick may be applied to the drop kick and the generation of maximal foot velocity and therefore ball

velocity is paramount. Holmes et al. (2006) and Ball (2010) reported no differences in the foot or ball velocity between the two kicking types. However the dynamics of the preparation and execution of the two kicking types may be different. One particular outcome is the significantly larger ball trajectories in the drop kick than the place kick (Holmes et al., 2006). Further investigation is required into the performance predictors of maximal drop kicks.

1.5.3.2 Training, muscular strength and muscle activation

From the kinematic sequence it is noted that kicking performance can be improved through technical adjustments. This section specifically assesses the effects of training, muscular strength and muscle activation on the performance outcomes of kicking.

Physiological improvement to muscular strength following resistance training (Manolopoulos et al., 2013) and a combined strength and kick coordination training intervention (Manolopoulos et al., 2006) have been shown to increase ball speed. The improvements were primarily made to the increase in kinematics angular velocities (Manolopoulos et al., 2006). Additionally, Fousekis and colleagues (2010) showed how players' strength profiles develop with longitudinal training time. While muscular strength and muscle mass are essential to kicking performance, it is likely that kicking requires more than strength alone. Manolopoulos et al. (2013) reported a regression model for ball velocity in the soccer instep kick. The regression model consisted of angular joint and segment linear velocities along with strength measures (Manolopoulos et al., 2013). The resistance training protocol had no effect on the electromyographic activity during the kicking sequence, which would suggest that the benefits are derived from the increase in strength and not muscle activation (Manolopoulos et al., 2013).

Australian football players that exhibit more accurate punt kicks have been shown to have more muscle mass than their less accurate counterparts (Hart et al., 2013, Hart et al., 2014). The differences in the leg characteristics were predominately in the stance legs suggesting that the dynamic balance control is more refined in accurate kickers compared to the less accurate kickers (Hart et al., 2013). The difference in accuracy may not be related to strength but rather the control of motor units. Having more muscle mass than fat mass enables a smaller percentage of the maximum capacity to be recruited to attain the same kick distance. This results in greater control of the muscle group as a smaller percentage of muscle fibers are used in the entire muscle pool to achieve the same outcome (Hart et al., 2014). Although the kicks assessed were punts, the results can be applied to most other kicks in rugby.

Kellis and Katis (2007) suggested that there might be a difference in the muscle activation patterns which may be able to distinguish between accurate and inaccurate kicks. One method to evaluate the segmental coordination and timing is through electromyography. In a sample of six trained soccer players, significant differences in quadriceps muscle activation were reported for kicks to different directions of the goals (Scurr et al., 2011). Specifically kicks made to the right displayed higher muscle activation than those directed to the left. Furthermore greater muscle activation was reported for targets to the top right compared to targets on the top and bottom left of the goals. However their participants were instructed to perform maximal kicks (Scurr et al., 2011). Therefore only the difference between accuracy in terms of goal positions can be concluded and not the differences between powerful and accurate kicks. A similar finding was presented by Katis et al. (2013) who found varying degrees of muscular activation in accurate kicks of differing heights. Therefore it is likely that the contribution of the muscles to kick accuracy may not be dependent on the size or the relative strength of the muscles, but the level and nature of muscle activation.

1.5.4 Scrum: a physical contest between opposing forwards

The previous two tasks are reliant on individual performances; arguably the kick is more of an individual skill as it requires only one individual to be involved. The scrum however is considered to be more of a unit performance as it requires input from multiple individuals.

It should be noted, that in theory scrummaging success is defined by retention or the gain of ball possession; or alternatively the gain of territory while in possession of the ball. These factors depend on three aspects: (i) the ability of a scrum-half to fairly deliver the ball to the hooker, (ii) the ability of the hooker to gain possession of the ball and to pass the ball backwards to other members of his team; and (iii) the ability of all the scrummaging players to drive the scrum forward. Unfortunately, in the modern game the first two factors are rarely contested facets of the game, and it is for this reason that the focus of this literature review (and the focus of literature on scrummaging success) is on the ability of scrummaging forwards to drive the scrum in a forward direction.

The scrum is a physical contest where eight players (forwards) from opposing sides are involved in a coordinated push for possession of the ball. Forwards can expect to spend 10% of the total game time in the high intensity static competition of the scrum (Duthie et al., 2003). An effective scrum requires the coordinative power of the team (Quarrie and Wilson, 2000, du Toit et al., 2005). Researchers have shown that scrummaging power is not only determined by the combined mass of the scrum but is also determined by the technique and timing of the force contributions of scrummaging players (Milburn, 1993; du Toit et al., 2005). To gain an advantage in the scrum is essential to a team's performance with more than 20 scrums occurring in an average game (Fuller et al., 2007, Roberts et al., 2014). The purpose of this section is to identify, based on recent literature: the performance outcomes of the scrum; kinematic and the physiological parameters related to scrum performance; as well as the injury concerns related to the scrum.

1.5.4.1 Scrum Performance Outcomes

Kinetics

Performance in the scrum is determined by kinetic factors, the forces exerted by the players. Various methods have been employed to quantify the kinetics of the scrum which include: instrumented scrum machines (Milburn, 1990; Quarrie and Wilson, 2000; du Toit et al., 2004; Wu et al., 2007; Preatoni et al., 2012) force platforms (Sharp et al., 2014) and shoulder mounted pressure transducers (du Toit et al., 2005; Cazzola et al., 2014; Preatoni et al., 2015).

The force exerted in the scrum is not simply a compressive force but is also composed of lateral and vertical forces (Milburn, 1990; Preatoni et al., 2013; Preatoni et al., 2014; Cazzola et al., 2014). The lateral forces experienced in the scrum have been attributed to the wheeling of the scrum (Milburn, 1990; du Toit et al., 2005). The lateral forces in the higher playing levels have been found to be directed towards the tighthead prop (right) (Preatoni et al., 2013). This slight lateral force could result in the rotation of the scrum as the duration of the contest continues. Milburn (1990) reported that the scrum as a unit tended to rotate along its length. The vertical or shear force has been associated with scrum collapses and front row players popping out of formation (du Toit et al., 2005; Preatoni et al., 2013). Upon engagement the vertical component was downwards and continually shifts upwards during the sustained phase (Preatoni et al., 2013). Even though these lateral and vertical forces contribute to scrummaging performance, the compressive force (forward pushing force) is of the most interest to investigators and coaches due to its obvious performance implications. Unless otherwise stated, in the discussion that follows, the scrummaging forces referred to are these compressive (forward) scrummaging forces.

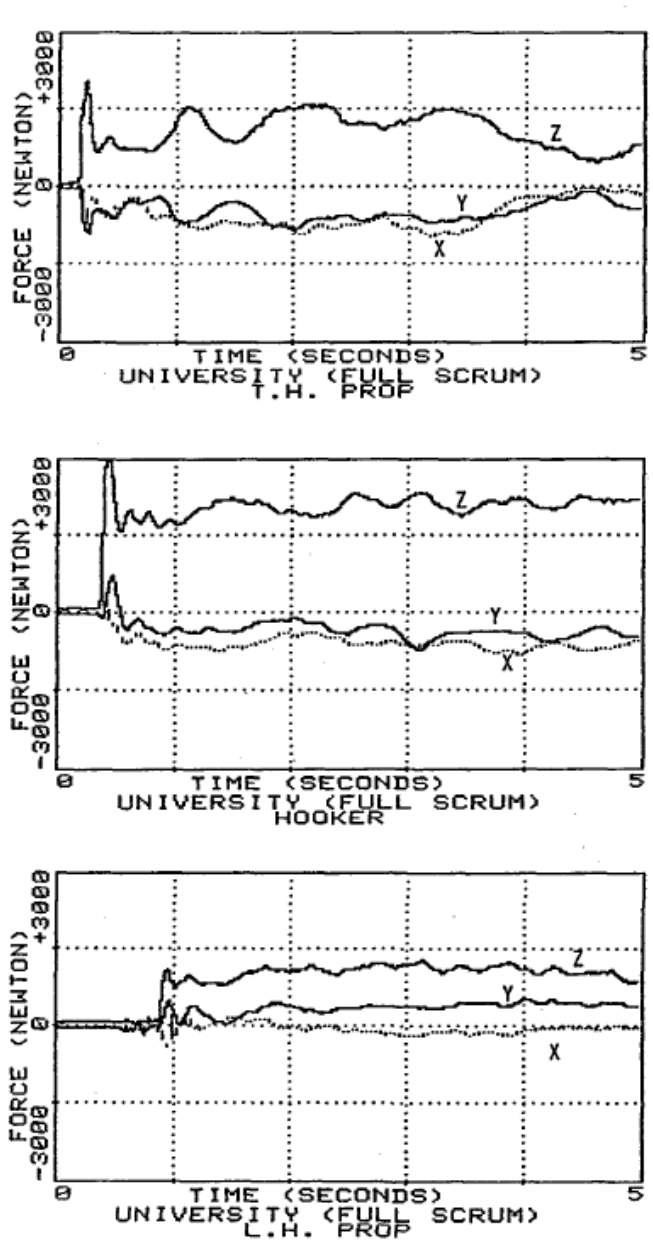


Figure 1.6: The forces generated during full pack university level scrummaging, from Milburn (1990) Figure 3 Force-time histories for each front-row forward in a university rugby union scrum (page 53; with permission Appendix 3). Tracing Z indicates the forward compressive force.

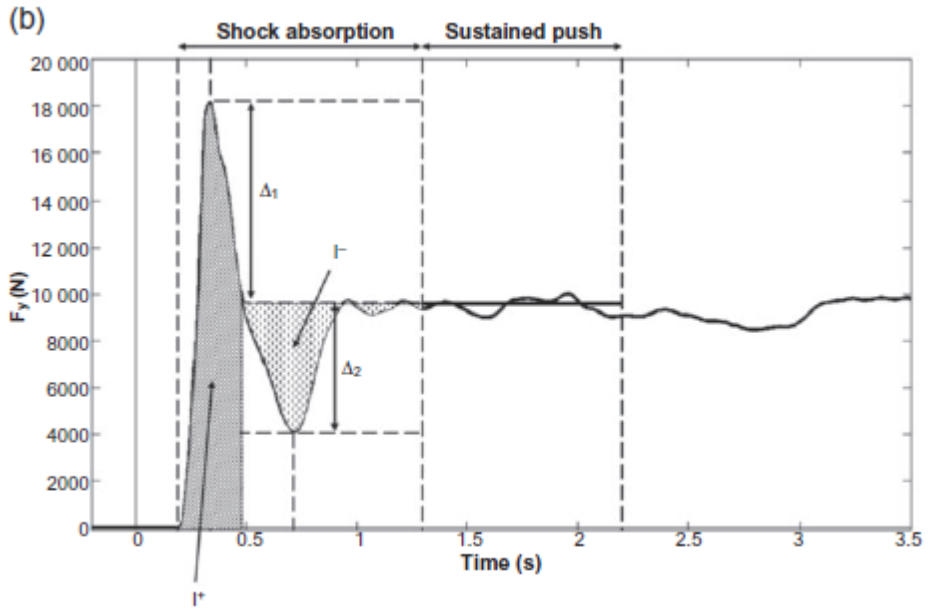


Figure 1.7: The force derived from a full scrummaging pack from Preatoni et al., 2013 Figure 2b: Typical force pattern (Compression) page e180 (with permission Appendix 4).

The two figures (1.6 and 1.7) show the development and sustainment of the team scrummaging forces. The forces exerted by, and through, the individual players in the front row are reported in Figure 1.6. It is noted that the tight-head prop (top insert) and hooker (middle insert) experience larger forces on scrum engagement than the loose-head prop (bottom insert, Figure 1.6). Additional the lateral and shear forces experienced by the tight-head and loose-head props are noticeably in different directions upon the scrum engagement. While these two graphs (Figures 1.6 and 1.7) were generated over two decades apart they exhibit a similar pattern in the phases of machine scrummaging. The description of the team scrummaging force, that follows, will be referring to the Preatoni and colleagues (2013) represented in Figure 1.7. The engagement of front rows onto a device results in the peak force and positive impulse during the shock absorption phase. The engagement results in the attainment of the peak force. Following the peak force there is a steady decline where the force is reduced as the players have a change in alignment between their shoulders and the

scrum machine pads (Milburn, 1993). The start of the sustained push is identified as the minor fluctuation around the sustained force magnitude developed from the coordinate effort of the team. The most noticeable difference between the Figure 1.6 (Milburn, 1990) and Figure 1.7 (Preatoni et al., 2013) is the magnitude of the peak force. Comparing the scrum force magnitudes from the university level players there has been an increase from 6540N (Figure 1.6) (Milburn, 1990) to 7771N (Figure 1.7) (Preatoni et al., 2013). This 1231N magnitude increase has been attributed to the increase in player size, technical abilities and playing level and will be discussed in the sections below.

Players of successively higher playing levels have been shown to display an increase in peak scrummaging forces (Milburn, 1993; Preatoni et al., 2013). The peak compressive force in the scrum has been shown to range between 8700N to 16500N while the sustained compressive force ranges between 4800N and 8300N depending on the playing level of the team (Preatoni et al., 2013). However the increase in the compressive force was not dependent on the weight of the packs, as pack weight also increased with playing level (Preatoni et al., 2013). It was concluded that teams of a higher playing level must utilize a better technical ability to generate greater scrummaging forces (Preatoni et al., 2013). Similarly the variation of the compressive force magnitude between teams decreases as playing level increases. This suggests that teams are more evenly match at the higher levels and utilise similar technical advantages. du Toit et al. (2005) reported that mismatches in force application exist within a school population. The data presented by Preatoni et al. (2013) also exhibits a large standard deviation for the school playing level, which suggests that a potential mismatch between teams exists between school level scrums. These differences could potentially be attributed to the masses of the packs and the developmental stages of the youth players.

The assessments of individual scrummaging force are largely limited by their current outcome measures which are the unidirectional measurement of the compressive force (Quarrie and Wilson, 2000; Wu et al., 2007; Sharp et al., 2014). As noted in the introduction of the scrummaging section, the compressive force is potentially the most important quantifiable force for performance. However it is not the only component of the exerted force, with the total force including shear and lateral components. Furthermore the exact position and directions of the forces cannot be determined though unidirectional force transducers.

The effects of different binding conditions

Previous research has investigated the effects of difference binding methods between the players (Milburn, 1993). The two major binding styles involved the second row players (locks) binding to their front row player either at their hips or by binding onto their shirts between their legs (crotch bind). Crotch bind related to increase in downward force of front row on engagement but not during sustained scrummaging (Milburn, 1993). However, the modern binding of the second row to their front rows only occurs in the crotch area and player are taught this method from age-group levels.

Over recent years the governing body of rugby has made minor adjustments to the rules regarding engagement of the scrum, in an attempt to reduce the compressive forces experienced on engagement and the chance of resulting injury. The need to make modifications to these laws was in part due to the growing number of catastrophic injuries resulting from the scrum. du Toit et al. (2005) used telemetric shoulder pressure transducers to investigate the scrum kinetics of different engagement types. The two engagement types were the full scrum engage and a staggered engage, where the units within the scrum (locks and loose forwards) would systematically join. This study is one of the few to investigate

scrum kinetics during live scrummaging. As predicted the engagement forces were the largest for the front row, regardless of the engagement type, however the full scrum engagement resulted in a larger force. The full scrum result is likely due to the additional mass and coordinative power which would produce a larger force, in comparison to the staggered method (du Toit et al., 2005). An interesting finding was that the engagement force magnitude had no effect on the sustained force magnitude. Therefore regardless of the engagement type used, teams were able to attain a similar sustained force magnitude (du Toit et al., 2005).

Preatoni et al. (2014) and Cazzola et al. (2014) evaluated five different scrum engagement techniques, with the aim of reducing the initial impulse force experienced during the engage while maintaining the sustained forces. The data was collected for individual teams scrummaging against an instrumented scrum machine. The five engagement methods are:

- Crouch-Touch-Pause-Engage (CTPE): the front rows do not establish the bind before initiating the scrum.
- Crouch-Touch-Set (CTS): Similar to CTPE except ‘pause’ was replaced by a silent non-verbal pause.
- “Fold in” technique: teams make no effort to generate momentum on the engage, are instructed on their posture and directed to apply power.
- Engagement number reduction: CTPE without either the eighth-man or without the loose forwards.
- PreBind/ ‘Crouch-Bind-Set’ (CBS): Front rows establish a firm bind on the ‘bind’ call.

The fold in technique reduced the engagement speed and peak compression force, mostly likely as a result of reducing the distance between the front row and the scrum machine

(Preatoni et al., 2014). Thus by simply reducing the distance between the two opposing scrums the total peak engagement force can be significantly reduced. While the reduced number of players on engagement reduces the engagement force it has numerous drawbacks. Firstly, the contest is hampered by reducing the total sustained force. Additionally scrum instability increases, due to the lack of contribution from the loose forwards (Preatoni et al., 2014). Furthermore the change in coordinative power of the team may cause buckling to occur (Preatoni et al., 2014). Preatoni et al. (2014) showed that the generation of sustained scrum forces are not dependent on the force of the engage phase. Additionally they suggest that the scrum engage could be detrimental to producing higher sustained forces. Therefore the initial scrum engagement should be more controlled if not entirely excluded. These studies were conducted on a single scrummaging pack contested against a scrummaging machine and might therefore have reduced validity in the live scrummaging contest. Additional studies into the binding sequences during live scrummaging were performance by Cazzola et al. (2014) using shoulder mounted pressure sensors to quantify the exerted forces in the live scrum.

Cazzola and colleagues (2014) showed that CTPE and CTS engagement forces produce a large rebound effect, which the authors suggest, could destabilise the scrum. Conversely by having the two packs in the prebind condition (each already bound to each other) would allow for a more stable platform and would require fewer postural changes. Cazzola et al. (2014) reported that scrum engagement forces could be reduced by 25% and 35% by using the Prebind (CBS) instead of the CTS and CTPE engagement calls. The reduction of the forces was only present during the engagement phases and the full 8 person scrums still managed to attain their normal sustained forces (Cazzola et al., 2014). Furthermore by using the Prebind, teams are less likely to lose their grip or slip on the one-off chance at a bind as compared to the CTPE and CTS methods. The Prebind condition reduced the distance and the

engagement velocities between the two front rows (Cazzola et al., 2014). These results would undoubtedly reduce the amount of scrum collapses and resets, therefore improving the quality of the game, and reducing the injury risk surrounding the scrum. During live scrummaging the Prebind has been shown to lower the hip range of motion, reduce the level of vertical movement of the front rows' shoulders and limit the variability in the positions of the props' CoM (Preatoni et al., 2015). All of these parameters are related to the stability of the scrum and therefore it can be concluded that the Prebind condition is undoubtedly the safest and most effective method for engagement between opposing front rows'.

1.5.4.2 Measuring individual scrummaging performance and their contributions to the team entire scrum

While the goal of the scrum is to maintain or regain possession of the ball as a unit, the individual positions have different tasks that culminate in a successful scrum. Quarrie and Wilson (2000) reported that a moderate relationship (r=0.49) exists between the scrummaging force of the full eight-person pack and the sum of individual scrummaging forces. Therefore the individual positional demands need to be established. This section will explore the kinetic contributions of the playing positions and the effects of player addition/removal on scrummaging kinetics and kinematics.

Milburn (1990; 1993) investigated the contributions of various playing positions within the scrum and found that the second row primarily aided the front row in the development of the resultant forward force. Their contribution assisted in producing nearly 50% more force compared to the front row in isolation. Additionally Milburn (1990) reported that the flanks' contributions to the scrummaging force were not substantial (less than 30%). du Toit and colleagues (2004) found that the individual force magnitudes differed between all playing positions. Milburn (1993) reported the average unit contribution to the compressive force magnitude, from the data of six studies, to be 42% front rows; 37% second rows and flankers

25%. In agreement with these previous findings, du Toit and colleagues (2004) showed that front rows contributed approximately 46%, locks 24%, and back rows 30% to the total exerted force.

During the sustained phase the front rows experienced a greater force than the other playing positions, irrespective of the engagement employed (du Toit et al., 2005). This finding is due to the compressive loads experienced by the two front rows. Not only would they experience the applied force from their opposition, but they would additionally experience the forces being applied by their second row players and flankers. For this reason, the two front rows would always experience a greater magnitude of force than other players.

Even though the different playing positions in the scrum exert various levels of force, they may intend to use the directional components of their forces to varying degrees. Milburn (1990) showed that while the loose forwards do not substantially contribute to the exerted force they do assist by improving the scrum stability. Similarly du Toit et al (2004) showed that the horizontal force during the sustained force was greater in the front rows compared to the other two groups. Likewise the difference was present between locks and back rows (du Toit et al 2004). The ensuing force derived from the individual contributions results in the mean angle of the application force being directed towards the opposition's tight head prop (du Toit et al., 2004). The differences in the componential forces are not limited to the horizontal forces. du Toit and colleagues (2004) showed that the front rows' vertical force component was greater than both locks and back rows; likewise locks had a greater vertical force component than the back rows. One reason behind these differences has been suggested that the front row requires vertical stability before being able to apply force (du Toit et al., 2004).

An effective scrum requires the coordinative power of the team (du Toit et al 2005). Subsequently researchers have shown that scrummaging power is not only determined by the combined mass of the scrum but is also determined by the technique and timing of the force contributions of scrummaging players (du Toit et al., 2005). du Toit et al. (2005) showed that the force of engagement and the sustained force of the front row were significantly greater than the locks and back rows, and suggested that this relationship was due to the larger mass and greater speed of engagement of the props compared to the other groups. In agreement with this were the results from Sayers (2007) who reported increased horizontal CoM velocities in the full eight-man scrum compared with the five-man (front row and locks) and three-man (front row) scrums. Additionally the distance that the players set-up from the machine was significantly higher when isolating the front row compared with the addition of the locks and full eight-man scrum (Sayers, 2007). A potential cause for the difference could be related to the masses of the pack when more players are added. As the mass of the pack increases the distance required to generate the force is likely to decrease. Furthermore the compressive force that the front rows will experience will be significantly increased with the addition of players. Therefore the reduced distance may be an integral trait the front rows use to reduce the stress they experience on engagement.

Strategies used to produce maximal force

The playing level of the team scrum has been shown to affect their maximal exerted force (Preatoni et al., 2013). Sharp et al. (2014) reasoned that players of different skill levels and experience used different strategies to achieve their maximal scrummaging forces. Specifically that junior players are more likely to use their body mass and not muscular strength to achieve their maximal force, while professionals may rely on the strength and activation of their erector spinae muscles (Sharp et al., 2014). This contention is unlikely as it is improbable that players of any skill level are passive scrummagers. It is more pertinent that

players, regardless of their level, actively scrum which requires not only body mass, but muscular strength and good technique. The relationship between body mass and scrum force has been reported by many researchers (Milburn, 1990; Quarrie and Wilson, 2000; du Toit et al., 2004; du Toit et al., 2005; Wu et al., 2007) but the data presented by Sharp et al. (2014) is less clear. They report that juniors have a positive relationship between force and body mass, while the seniors have a negative relationship and no relationship was present for the professional group (Sharp et al., 2014). Furthermore, Preatoni et al. (2013) reported that the magnitude of the scrummaging forces were still larger for high playing levels when team weight was accounted for. Therefore the high playing levels must utilise technical performance to achieve their scrummaging advantage. These technical parameters may be based on movement strategies (kinematic) (Sayers, 2007, Preatoni et al., 2012) or achieved through the coordination of exerted forces within the scrum (du Toit et al., 2005). The sections to follow will explore: the effects of body positioning (kinematics); muscular strength and activation; and the interaction between the turf and boot in relation to scrummaging performance (i.e. scrum kinetics).

1.5.4.3 Kinematics of the scrum

The laws surrounding the scrum have resulted in the development of a highly technical component of the game. Coaches and individuals strive to find the competitive edge through the use of various technologies. One method currently used is kinematic analysis, from which angular and scalar displacements and velocities of a players' body parts can be obtained. The proceeding section summarises the current literature surrounding scrum kinematics related to performance. The majority of scrum kinematics are focussed on individual performance. Kinematically scrum performance is determined by two major factors, the trunk and the legs. The trunk is a contributing factor to scrummaging performance as it is the channel through

which the force is transferred to the opposition, while the legs are the primary contributors to the development of the scrummaging force.

Kinematic description of the scrum sequence

The individual scrummaging sequence begins with the player in a crouched position. In this position the individual will have their feet firmly on the ground with a large degree of flexion at the knee and a large hip flexion. Sharp et al. (2014) suggested that the crouch position provides the stability prior to the engage. Sayers (2007) showed that while players adopt different starting positions their kinematics upon engagement do not significantly differ. Upon the call of engage the player will have rapid extension of the knees and hips (Sayers, 2007). It is during the engagement phases that the generation of maximal force is usually exerted (Preatoni et al., 2014 Cazzola et al., 2014). The trunk will normally be slightly above the parallel with the ground (Sayers, 2007). Players will bind to their opponents by griping onto their jerseys, and upon the call from the referee will engage with the opposing front row. Following the engagement and the rebound phase (which is yet to be observed kinematically) is the sustained force phase (Preatoni et al., 2013). During the sustained phase the lower limbs exhibit a large degree of extension (Quarrie and Wilson, 2000; Wu et al., 2007), and the trunk will gradually increase above the horizontal. While the players may seem to be static during a competitive scrum there will be continual activation of the muscles to maintain, if not produce more force (Sharp et al., 2014). When a scrum is moving players may exhibit a marching of the limbs, whereby they will methodically flex an individual leg to step forward. This process allows for the contraction of the quadriceps and the further generation of force. Interestingly the kinematic velocities shown during the scrum duration lacks the proximal to distal segment sequencing shown in other tasks (Sayers, 2007). The ideal scrum position has been reported by Milburn (1993). He suggests that the head (and neck), trunk and legs all be aligned parallel to the direction of the intended force.

Additionally, it was suggested that a greater angle (lateral view) between the trunk and legs (hip angle) results in a larger force (Milburn, 1993).

The positioning of the trunk

Milburn (1990; 1993) reported a surprising finding, that the magnitude of the forces experienced during the engagement of the two front rows exceeds the threshold for spinal injury. He attributes this directly to the speed of the engagement and the mass of the two packs. Therefore he advocates that players need to have the correct alignment of their heads, necks and trunks and that they require suitable muscular strength to maintain the required positions in the scrum formation (Milburn, 1990). Front row players are instructed to have their shoulders above their hips (when viewed in the sagittal plane) in an attempt to prevent the scrums from collapsing. Consequently du Toit and colleagues (2004) suggested that the front row make a deliberate effort to scrum higher up as to prevent the scrum from potentially collapsing. Furthermore du Toit et al (2004) states that the front row requires vertical stability before being able to apply force. The ability of the front row to maintain a horizontal trunk position (parallel to the ground) is affected by the addition of the second row players (Sayers, 2007). Sayers (2007) showed that the front row had a thoracic angle of 0° when engaging a scrum machine, and how this value increased to 6° when the second row players and the loose forwards were added. These results may show how the balance of the front row players' is affected by the addition of the remaining scrum players. While the front row players require an above horizontal trunk position, locks and loose forwards may have a continuum of thoracic angle when bound to the scrum. Saletti et al. (2013) showed that the thoracic angles are different for the various playing positions during the scrum. The transmissions of force have been reported to be multidirectional, depending on the playing position. As the thorax is the major structural component in the force transmission, its position would greatly affect the force direction.

Leg kinematics

Quarrie and Wilson (2000) investigated the anthropometrical, physiological and biomechanical contributors to individual and team scrummaging performance. Biomechanically they found no significant relationships between leg joint kinematics and individual scrum force exertion. Wu et al. (2007) assessed the potential relationships between posture and individual scrummaging force production. They developed an instrumented scrum machine and simultaneously recorded body kinematics and scrum kinetics under different conditions. Significant correlations were present between the hip (r=-0.47), knee (r=-0.51) and the ankle (r=-0.70) and the individual scrummaging forces (standardised as a percentage of the body mass). Wu et al. (2007) continued to report that the upper two quartiles of the force magnitudes were produced with lower extension values of the leg joints compared to the lower two quartiles which had higher leg joint extension values. The lower extension angles would suggest that eccentric contraction of the legs must occur to develop force.

The similarities in the individual kinematics between the Quarrie and Wilson (2000) and Wu et al. (2007) studies suggested further that there are limited techniques to scrummaging (Table 1.2). A comparison of the body kinematics reported in Table 1.2 displays a similar degree of hip and knee flexions. However the Quarrie and Wilson (2000) hip flexion data does show a larger standard deviation, which may be attributed to the greater sample size when compared to the Wu and colleagues (2007) dataset. An assessment of the knee flexion reveals that both groups attained similar values. The greatest difference between the two datasets is the ankle flexion angle. Sayers (2007) reported that a similar body position was adopted by the high level players prior to engagement and during the scrummaging duration. There would have to be limited movements and body positions that an individual could assume to perform an effective scrum.

Table 1.2: Comparison of kinematic variables for the legs at maximal force exertion during individual scrummaging.

	Quarrie and Wilson, (2000)	Wu et al., (2007)
Sample size	56	10
Hip (°)	123 ± 24	121 ± 7
Knee (°)	107 ± 13	101 ± 18
Ankle (°)	78 ± 11	62 ± 16

Positioning of the feet and scrummaging height

The Wu et al. (2007) investigation was focussed on the development of individual scrummaging forces resulting from different engagement heights and positioning of the feet. Anecdotally it is recommended that scrummaging at a lower body height is desired. However a lower body position may cause the individuals to make minor postural adjustments which could destabilise the scrum. Interestingly Wu et al. (2007) reported that individuals exerted more force at 40% of their body height compared to 36% and 38% of their body heights. Assessing live scrummaging under different engagement methods Cazzola et al. (2014) reported that the front rows had a higher shoulder height in the Prebind condition compared to CTPE and CTS conditions, resulting in more stable scrums.

An individual preference to scrummage with their feet in either parallel or cross-foot positons may be presented by players. Assessing the leg kinematics, it is noted that in the parallel foot position there were no differences in the angles between the different body height positions (Wu et al., 2007). These results indicate that less extension of the legs, when in the parallel position results in greater force exertion. Comparing the cross-feet position to the parallel feet position they reported no significant difference in the exerted force positions (Wu et al.,

2007). However they do mention that in the cross-feet position a profile in the force tracing exhibits a double peak, compared to the single peak in the parallel feet position. In the cross-feet position the posterior hip extension was significantly correlated to exerted force (r=0.44).

The effects of different engagement styles on scrum kinematics

In the preceding sections it was shown how the engagement method of the scrum can reduce the peak engagement force while maintaining the sustained kinetics (Preatoni et al., 2014 Cazzola et al., 2014). Cazzola et al., 2014 assessed the changes in the scrummaging kinematics resulting from these various scrum binding types. The different scrum engagement methods resulted in a change in the range of motion of the hip joint (Cazzola et al., 2014). Tight-head props showed a reduction in the hip range of motion between the CTPE and the PreBind whereas loose head props displayed a reduced hip range of motion between the CTPE and CTS conditions (Cazzola et al., 2014). No significant differences were present for the loose head props between the PreBind and the CTPE and CTS conditions. Furthermore while the differences in the tight-heads' ranges of motion were exhibited for both scrummaging packs, the loose heads' difference was only for the one pack (Cazzola et al., 2014). The differences reported in the hip ranges of motion may be attributable to the distance between the two front rows and the velocities that each engagement method allows for. Crucially players are able to maintain safe scrummaging technique regardless of the engagement methods employed (Cazzola et al., 2014). Scrummaging safety is usually defined by the alignment of the head and trunk thus the term 'spine in line' is widely used throughout the coaching world and amongst players alike.

The number of players in the scrum affects the timing and coordination of the effort, with peak leg extensions occurring at different time points prior to the scrum engagement (Sayers, 2007). Larger angular velocities of the hip extensions were observed when front rows and

locks scrummaged compared to the isolated front rows and the full pack. The same effect was observed with the full pack displaying larger angular velocities of the hip extensions than the isolated front row (Sayers, 2007). Equally greater knee extension velocities were reported for the isolated front row compared with the addition of locks, and the full pack (Sayers, 2007). Additionally the full pack exhibited greater knee extension velocities than the combined front row and locks unit (Sayers, 2007). These two differences are likely to affect the forces generated and impact of the engagement on the front rows. The decreased velocity of the front row players when scrummaging as a full pack might be a technique to reduce the stress inherent to scrummaging engagement.

Attacking or defending scrums

A fundamental area of difference in the scrummaging kinematics may be between attacking and defending scrums. A defending scrum is defined by the lack of force exerted when compared to the dominance of the attacking scrum (Flavell et al., 2013). Attacking scrums were based on two players competing against a single player, and that the two players would generate more force than the single player. Greater extensions of the hip joints were exhibited during defensive scrums compared to attacking scrums (Flavell et al., 2013). The larger extension of the hip was present throughout all the phases of the scrum. Differences in the kinematics of the legs are present between attacking and defending scrums (Flavell et al., 2013). These differences may be a result of the mismatch in the exerted forces. In a two-on-one contest the two players are able to exert a larger force than the single player, and therefore the single player is likely to be displaced backwards. This was evident from the peak flexion acceleration of the knee joint, showing that in an attacking scrum the acceleration occurred from a position in which the knee joint was more extended (Flavell et al., 2013). The attacking scrum would allow for more movement to occur as the two players have double the amount of feet on the ground and thus lifting a foot from the turf would

result in a beneficial foot placement, allowing for a greater potential extension of the knee and hip. Conversely the defending player would have to attempt to maintain their position firmly on the turf. By doing so they would only be able to make minor adjustments to their kinematics. Finally the kinematics that were exhibited during defensive scrummaging may result in injury to the muscles of the shank (Flavell et al., 2013), raising the issue for players as how to go about successfully defending a scrum.

1.5.4.4 Muscular factors and scrummaging force generation

Milburn (1990) and more recently Sharp et al. (2014) have advocated the need for players to have a high level of functional strength to exert maximal force and maintain the correct body posture while scrummaging. The assessment of strength and scrum force production has been investigated with surprising results. Sharp et al. (2014) assessed the muscular strength of rugby players of three different playing levels (professional, senior amateur and juniors) using maximal isokinetic strength tests. They reported no significant differences across the three groups. In relation to performance, professional players displayed a negative correlation between trunk flexion and maximal horizontal force (Sharp et al., 2014). Juniors presented a negative relationship with the right knee flexion and maximal horizontal force (Sharp et al., 2014). No significant relationships were observed for the senior groups between maximal horizontal force and the strength measures for leg and trunk extensions and flexions (Sharp et al., 2014). Interestingly the significant correlations for maximal horizontal force were all negative for the respective body segments (trunk and knee flexions). This is likely due to the nature of the scrummaging sequence, which requires extension of these segments during the engagement phase. Quarrie and Wilson (2000) showed that individual scrum force is related to a maximal isokinetic knee extension torque at 1.05 $rad.s^{-1}$ (r=0.39) and 3.14 $rad.s^{-1}$ (r=0.41). Additionally they showed that individual scrum force is related to anaerobic power

(r=0.51) (Quarrie and Wilson, 2000). A simple field test for lower body strength, the vertical jump test, was not related to individual scrummaging force production (r=-0.13) (Quarrie and Wilson, 2000). While these two studies have predominately focussed on the lower limbs, the trunk musculature has been shown to be important in the transmission of the forward force during scrummaging (Cazzola et al., 2014, Sharp et al., 2014).

To better understand the physiological requirements of scrummaging electromyography of various muscles has been investigated. Due to the technical complexity of the research conducted on muscular activity and the difficulty of applying such methodology to a dynamic scrum, data from such studies is limited. To simplify the difficulties of measuring the electromyography in a full eight-person scrum, individuals have been investigated. The electrical activity of the lower back (erector spinae) has shown more activity than the quadriceps and hamstrings during the engagement phase (Sharp et al., 2014). Furthermore during the same phase, the quadriceps muscles display more activity than the hamstrings (Sharp et al., 2014). Both of these findings were observed regardless of the playing levels of the individuals. It would seem as though the biggest contributors to scrummaging force production, regarding the muscle activity is derived from the quadriceps and the lower back. However at maximal force only the muscle activity in the erector spinae were correlated to the individual scrummaging force. This result was only observed in a group of professional players (Sharp et al., 2014). No other muscular activities were related to the scrummaging performance. The authors suggested that the lower level playing groups (juniors and amateurs) must use different strategies to produce their maximal forces.

Cazzola et al. (2015) investigated the muscular activity of the spinal musculature (sternocleidomastoid and erector spinae) under different scrum engagement conditions. They compared the scrum binding calls (current: crouch-bind-set (PreBind) and old: crouch-touch-set (CTS)) and a live two-on-one scrummaging drill. As the scrum duration progressed the

activities of the sternocleidomastoid and erector spinae decreased. Interestingly the muscle activity of the two observed muscles had lower activity during the older (CTS) than the current (PreBind) calls. The authors propose that the differences in the muscle activities between the two binding calls may be a result in the change in the postures of the individuals (Cazzola et al., 2015). They suggest that the crouch-bind-set call may prepare the upper part of the spinal column for the active engagement of the scrum (Cazzola et al., 2015).

As expected the muscular activity was higher in the live scrummaging condition compared to those on the scrum machine. The authors resolve that the spinal muscle activation must be a result of the load experienced on the players' shoulders (Cazzola et al., 2015). During live scrummaging the erector spinae muscles serve to stabilize the trunk. These parameters while essential to the understanding of the muscular activity during scrummaging are likely to be underestimated as the contribution resulting from the additional players may cause for greater activation during live eight-man scrummaging. It is possible that the addition of substantial mass to the system would result in higher muscular activity during the engagement and sustained force phases. Similarly the front row players may exhibit a higher fluctuation of muscle activity during the sustained phase, in an attempt to maintain their body positions while experiencing compressive forces.

1.5.4.5 Interaction with the turf

Newton's third law of motion would suggest that the exerted force developed in the scrum is a result of the interaction between the feet and the turf. Quarrie and Wilson (2000) reported an unpublished observation by Peters, Jevon and Williams from Liverpool John Moores University, UK that scrummaging forces are larger (2500 ± 420 N) when the entire foot is in contact with the ground compared to when just the toes are in contact (2280 ± 420N). The

interaction between the foot and the playing surface must affect the magnitude of the scrummaging force. If the friction of the system isn't adequate the players will have to make adjustments to their legs, resulting in them lifting their feet off the ground and reducing the force. Milburn (1998) suggested in his review of footwear and injury in rugby union that the studs should provide enough traction to produce substantial forces. In the modern game many Northern Hemisphere teams use artificial pitches which are less likely to degrade throughout the game and allow for a stable base on which scrums can be performed. Swaminathan et al. (2016) reported that scrums were more stable on synthetic turfs compared to natural turf. This conclusion was based on the fewer postural changes experienced by the hooker (Swaminathan et al., 2016). The quality of the turf (allowing for better traction) is likely to reduce the number of scrums collapsing therefore reducing the likelihood of sustaining an injury and improving the overall game play.

In summary it has been shown that scrummaging performance is multifaceted and attributable to parameters both biomechanical and physiological. The various investigations have highlighted the variation in and the effect of different binding conditions on the performance outcomes. The scrum has been identified to be a highly technical component of rugby, which is: positional specific; requires developed strength, and can possibly result in injury. Perhaps the most conclusive summary is reported by Quarrie and Wilson (2000) that heavier, more powerful individuals with larger hip extension angles are most likely to produce the maximal individual scrum force.

The previous sections have shown how performance can be measured when related to various tasks specific to rugby. During the progress of the 80 minutes of a rugby game, however, optimal performance may not always be achievable. A major contributor to reduced

performance is fatigue. In the section that follows a global definition of muscle fatigue is provided; quantitative methods for assessing fatigue are considered and the effects of fatigue on performance are discussed.

1.6. The effect of fatigue on sports performance

1.6.1. Definition of fatigue

The definition of fatigue is widely disputed (Weir et al., 2006; Knicker et al., 2011) therefore for the purpose of this section and thesis, muscle fatigue (fatigue) is considered to be the state at which the muscle is no longer able to produce maximal force and velocity (Westerblad et al., 2002; Hunter et al., 2004; Fitts, 2008). Exercise induced psychological fatigue is a feature of one of the studies in this thesis (chapter 8) and will therefore briefly be discussed in a later section.

Hunter and colleagues (2004) stated that muscle fatigue is a multifaceted process that is dependent on the performed task, physical environment and the muscle group involved. The development of muscle fatigue relies on neuromuscular, proprioceptive and psychological factors. There are two main theories in the development of muscle fatigue (Weir et al., 2006; Knicker et al., 2011). The first and most pertinent is the central governor theory which suggests that the brain mediates the control of the muscles in the fatigued state by reducing the descending drive (Stirling et al., 2012) or reducing the afferent synaptic input (Enoka et al., 2011). The second theory known as peripheral fatigue suggests that metabolite accumulation within the muscles alters the contributing factors required for a maximal contraction (Petersen et al., 2007; Stirling et al., 2012). The development of fatigue is possibly not isolated to only one of these proposed mechanisms but would rely on inputs and mediation from both sources suggesting that both muscular and neural mechanisms are

impaired during fatiguing contractions (Hunter et al., 2004). Despite this contention, Fitts (2008) suggested that molecular factors contribute and ultimately control the force, velocity and power generated within muscle fibres, asserting the ultimate role of peripheral mechanisms. However it could be argued that the two models independently assess either the physical or emotional state (Weir et al., 2006). However the manifestation of fatigue is unlikely to be a result of one of these mechanisms but rather a combination of both models (Knicker et al., 2011).

The development of fatigue and its consequences are dependent on the tasks performed during a fatiguing activity (Apriantono et al., 2006). The effects of fatigue may be short lived and therefore Froyd and colleagues (2013) suggested that the measurement of performance outcomes should occur as soon as possible following the fatigue intervention in order to gauge the role fatigue may play on muscular work. Furthermore the major reductions in the performance of the specific tasks may occur in the early stages of the activity (Froyd et al., 2013).

As reported in the preceding section, fatigue can manifest in multiple ways and can be assessed through the measurement of concentrations of physiological metabolites, alteration to kinematics or muscular performance, and subjectively through the use of perception scales. The following sections will briefly discuss these aspects related to the quantification of fatigue.

1.6.2 Markers of muscle damage or fatigue

Fatigue was defined as the failure of muscle to effectively perform the desired task. The accumulation of metabolites (see peripheral theory, above) can often be measured and may therefore be objective indicators of fatigue. Additionally, in many forms of exercise, damage is caused to the muscle cells which results in metabolites appearing in the blood and can therefore be used to assess the level of fatigue (Finsterer, 2012). Two widely used (lactate and creatine kinase (CK)) and one less frequently used (urea) markers of fatigue will be discussed regarding their physiological mechanisms, use in sports research generally and specifically in rugby.

1.6.2.1 Lactate

The progression of exercise above the aerobic capacity of a muscle results in the accumulation of anaerobic metabolites. One such metabolite is lactate, which exits muscle fibres along with hydrogen ions forming lactic acid. Lactic acid is a strong biological acid which may once again dissociate into lactate and a free hydrogen ion (Westerblad et al., 2002). Although circulating lactate can be metabolised for energy production (and is therefore a molecule which alleviates fatigue), its presence is an indicator of general metabolite accumulation and therefore an indicator of fatigue.

Blood lactate has been shown to increase following sporting activities and increased circulating values are dependent on the intensity and duration of the activity (Krustrup et al., 2003; Atkins 2005; Coutts et al., 2007a). Following a competitive rugby game blood lactate (Takarada, 2003) and the enzyme lactate dehydrogenase (Mashiko et al., 2004) have been reported to be increased in blood concentration. Note that such an increase in blood lactate may originate from general metabolite accumulation from normally functioning cells (as

described above) or from the lysing of cells containing lactate. The presence of lactate dehydrogenase, which is normally an intracellular enzyme and not found in blood plasma, can only be a marker of the latter breakage of cell walls. It has been suggested that the intense static components of rugby, in which forwards are often involved, are responsible for the increased anaerobic fatigue markers (McLean, 1992; Deutsch et al., 1998; Austin et al., 2011). Recent data from Morel et al. (2015) would dispute that the static components of rugby are solely responsible for the increased blood lactate. They reported increases in blood lactate following scrum repetitions however the increase appears to be progressively lower in scrummaging compared to simulated mauling and sprinting (Morel et al., 2015). The high lactate values are therefore likely to result from the combined high intensity static exertions and the sprints that occur. However the demands of running, if sub-maximal, would allow for the lactate in the blood to be metabolised. Significantly higher blood lactate concentrations have been reported in contact simulations compared to non-contact simulations (Mullen et al., 2015). The resulting higher lactate values following a contact simulation may arise from the intensity of the activity and not from the trauma of the collision. Therefore measuring blood lactate may give an indication of the multiple exertions experienced during a rugby game.

1.6.2.2 Creatine kinase

Creatine kinase (CK) is an intramuscular enzyme that catalyses the conversion of creatine and adenosine triphosphate (ATP) to phosphocreatine and adenosine diphosphate (Brancaccio et al., 2007). Due to its energy catalysing action CK (and particularly a muscle specific isoform CKMM) is predominately found in skeletal muscle. In addition to CK leaking out of broken muscle cells, increasing exercise intensity has been shown to cause permeability changes in the muscular membrane, allowing for the leakage of CK into the

interstitial fluid (Brancaccio et al., 2007). The CK is then transported by the lymphatic system back into the blood for clearance (Brancaccio et al., 2007; Smart et al., 2008).

CK concentrations are known to significantly increase in the plasma, following intense bouts of exercise (Brancaccio et al., 2007; Azizbeigi et al., 2015; Wiewelhove et al. 2015) and specifically a rugby game (Takarada, 2003; Mashiko et al., 2004; Smart et al., 2008; McLellan et al., 2010; McLellan et al., 2011; Johnston R. et al., 2015). The increase in CK following a rugby game has been attributed to the physical impacts between players, specifically the tackle (Takarada, 2003) and scrum (Smart et al., 2008) and is thought to be related to the intensity of collisions (Mashiko et al., 2004; McLellan et al., 2010; McLellan et al., 2011; Mullen et al., 2015). Similarly the elevated CK values may be dependent on the playing position of the individual (Jones et al., 2014).

However CK is known to increase following non-contact activities such as: soccer (Fatouros et al., 2010; Stone et al., 2016); small-sided games (Johnston R. et al., 2014); intense exercise (Azizbeigi et al., 2015; Wiewelhove et al. 2015); repeated sprints (Taylor et al., 2015; Johnston M et al., 2015); running (Martin et al., 2015); and walking (Tsatalas et al., 2010). Because increased blood CK concentrations are major indicators of muscle damage, independent of being potential indicators of fatigue, increased blood CK concentrations may underestimate the effects of fatigue, due to the mechanism that results in CK being present in the blood. CK normally peaks hours after the intervention (Brancaccio et al., 2007) and it has been suggested by Twist and colleagues (2012) that CK is not representative of fatigue when analysed in isolation. Therefore a more immediate marker of muscle damage, and specifically fatigue, is required.

1.6.2.3 Urea

The production of urea occurs in the liver when amino-acids undergo degradation. The production of urea is closely associated with the amount of ingested protein (Weiner et al., 2015). The association between urea and fatigue is linked to the depletion of glycogen and the use of skeletal muscle catabolism as the main component of metabolism. (Wiewelhove et al., 2015).

Blood urea concentration has been reported to increase following a soccer game (Bangsbo, 1994; Andersson et al., 2008), and high intensity training (Kyröläinen et al., 2008; Wiewelhove et al., 2015). Similarly blood urea has been shown to increase following a rugby game (Mashiko et al, 2004). Unlike the presence of CK in the blood, the increased circulating values may not be an indication of the physical impact experienced from running or the collisions inherent to the game. The elevated urea values may represent the change in energy demands, shifting from readily available glucose and glycogen to proteins (Mashiko et al, 2004; Coutts et al., 2007b; Andersson et al., 2008; Kyröläinen et al., 2008; Wiewelhove et al., 2015). The evidence for this mechanism was endorsed by Higton et al. (2013) who reported that ingestion of a combination carbohydrate-protein drink resulted in higher blood urea concentration values. It is possible that an individual who is depleting their glycogen and their other readily available sources of energy may begin to use catabolic pathways which produce urea. It is possibly for this reason that urea is emerging as a blood borne marker of fatigue.

1.6.2.4 Heart rate and heart rate variability

Physiologically exercise will result in the elevation of heart rate. The increase in heart rate occurs due to the increase in muscular oxygen demands. Oxygen is necessary for the

production of energy via the aerobic pathway, that is, the conversion of pyruvate to Adenosine Triphosphate. Vital oxygen is transported via the blood attached to erythrocytes and the rate of oxygen delivery is dependent on the mechanical action of the heart. A simple method of recording the mechanics of the heart is through the heart rate.

Measuring the heart rate is an easy and inexpensive method to determine the intensity of a prescribed activity. Moreover the relationship between the maximal oxygen uptake and heart rate has been used to determine VO_{2max} (Achten and Jeukendrup, 2002). Indeed the heart rate has been reported to be elevated following physical activities of various intensities (Impellizzeri et al., 2005; Atkins, 2005; Coutts et al., 2007a). Not only can the heart rate indicate exertion levels, but more in depth analysis of variability of the heart rate can be used to determine overexertion (Impellizzeri et al., 2005). Heart rate variability (HRV) is the measurement of time variation between heart beats, usually defined by R-R interval on an electrocardiograph or a heart rate monitor (Weippert et al., 2010). HRV is widely accepted as a non-invasive method to estimate the autonomic regulation of the heart (Malik and Camm, 1990), and a decrease in HRV has been related to exercise intensity (Saboul et al., 2016).

1.6.2.5 Perceived psychological fatigue

Perception of fatigue is acquired by the individual through emotional and physiological disturbances. In relation to performance the psychological perception of fatigue can manifest through acute or chronic mechanisms. Specifically, the effects of game situations can be describes as having an acute effect on psychological performance. Previous research has shown how emotions change during the course of a game (Campo et al., 2016) and are influenced by the individuals own perception of performance (Robazza & Bortoli, 2007; Campo et al., 2016), and the cumulative effects of previous games and experiences leading

up to the game (Grobbelaar et al., 2011). Moreover, the location of game, either home or away has been associated with a change in mind set (Kerr & van Schaik, 1995; Terry et al., 1998), with home games more likely to have reported positive mind sets, improved self-confidence and reduced anxiety (Terry et al., 1998).

The degree of physical and mental exertion is related to the length of the task, intensity and previous experiences (St Clair-Gibson et al., 2003) The perception of fatigue can be measured using a subjective rating scale (Impellizzeri et al., 2005; Knicker et al., 2011). Rating scales can be defined using numerical or descriptive terms. The 6-20 Rate of Perceived Exertion (RPE) scale was developed by Gunnar Borg in 1970 and is a strong integrator and determinant of internal psychological and physiological exertion (Eston, 2012). The numbers are anchored by verbal expressions that are easily understandable and synonymous with the exertion experienced. The uneven nature of the scale (6-20) is by design as the select numerical value when multiplied by 10 approximates to the corresponding heart rate (Borg 1982). Application of the 6-20 RPE scale has been shown to accurately report the linear increase in perceived exertion from a constant high intensity run (Doherty et al., 2001).

The use of this scale and its derivatives have been shown to determine the intensity of a sports training session (Impellizzeri et al., 2005; Lockie et al., 2012; Oliver et al., 2015) and track long term development of fatigue over a season. Various other scales that can be used to measure fatigue have been reported to be closely associated with: heart rate (O'Sullivan, 1984); lactate threshold (DeMello et al., 1987); the decline in energy stores; oxygen consumption (Eston and Williams, 1988) and increasing cellular acidity (Knicker et al., 2011).

1.6.3 Kinematic changes resulting from fatigue

Fatigue may be associated with a subsequent reduction in the muscular activation and therefore reduced power output (Knicker et al., 2011) which may result in changes in the kinematic patterns used by an individual to perform a task. It has been suggested that during fatigue the body will automatically activate compensatory mechanisms to reduce the propagation of further muscle pain by stimulating the use of alternate accessory muscles (Paschalis et al., 2007). Brooks and colleagues (2008) suggested that muscle fatigue may alter the player's technique which puts them at further risk of injury. However it has been found that technical performance during fatigue may deviate from the non-fatigued state rather than completely deteriorate (Knicker et al., 2011). This observation best describes the different strategies that individuals can use depending on the level of fatigue that they may experience to effectively perform the desired task.

1.6.4 Fatigue in rugby

It is clearly evident from the physiological demands of rugby (outlined in section 1.3.4) that the development (physiological and psychological manifestations) of fatigue is dependent on the playing position of the individual. The effects of fatigue on team performance in rugby are likely to vary amongst players largely due to the different positional demands of the individual players. As forwards and back have different demands, fatigue may manifest through the static (scrum, ruck) or dynamic (mauling, sprinting) high intensity repeated efforts. Additionally the development of fatigue may be compounded by the effects of muscle damage resulting from the collisions (Johnston et al., 2014; Mullen et al., 2015). Markers of fatigue, both psychological (Mashiko et al., 2004; Robazza & Bortoli, 2007) and physiological (Takarada, 2003; Mashiko et al., 2004; Smart et al., 2008; McLellan et al., 2010; McLellan et al., 2011), have been shown to increase following competitive rugby

games. Additionally, both physical and technical performance has been reported to decrease in the final stages of a rugby league match (Kempton et al., 2013). This section will focus on the decline of physical and technical performance resulting from interventions based around rugby (union and rugby league), identifying physiological variables and performance indices that have been discussed in the previous sections.

Multiple interventions have been used to investigate the effects of match induce fatigue. Arguable the most accurate intervention would be a competitive match. Amongst the first to assess the demands of competitive rugby matches were McLean (1992) and Deutsch and colleague (1998). Most studies, using game intervention, have shown reductions in muscle strength and power measures and declines in mood ratings, particularly those related to the perception of fatigue (Twist et al., 2012; West et al., 2014; Oliver et al., 2015). However, a match has multiple variables that cannot be standardised. For this reason, various studies have used repeatable protocols that mimic the specific movements of rugby (either league or union). A standardised method of inducing match related fatigue, specifically in forwards, is the BURST (Roberts et al., 2010) (refer to section 1.4.9). A modified version of the BURST will be used to assess the effects of match related fatigue on individual scrummaging performance in Chapter 8 of this thesis.

Both forms of rugby are intermittent and involve multiple repeated efforts of physical exertion. The repeated efforts of tasks involve: multiple running efforts (sprints) and contesting mauls and scrums. Therefore, fatigue can manifest from the culmination of various events. Indeed, repeated sprints have been shown to reduce countermovement jump height while resulting in increased muscle soreness, blood CK and lactate (Johnston et al., 2015). However, this intervention is not specific to rugby as it neglects the physically demanding task such as scrummaging, mauling and the inevitable collisions between players.

Morel and colleagues (2015) used three increased intensity protocols to investigate their effects on their performances. The three protocols were repeated sprints of 30m, simulated maul (dynamic push against weight scrum machine); and a simulated individual scrum (static push against weight scrum machine). Their results indicated that the repeated efforts a reduction in the performance values (first attempt vs fifth attempt). Interestingly, the concentration of blood lactate was reported to be higher for the repeated sprints and simulate mauls compared with the simulated scrums. Additionally, the RPE was higher for the simulated scrum compared to the simulated maul and repeated sprints. Morel and colleagues (2015) inferred that the development of fatigue resulting in the decline of task performance were derived from different mechanisms. Specifically, that the static task (scrummaging) was reduced due to reduce muscle activation; and the dynamic task (repeated sprints) had reduced performance due to metabolic disturbances, the increased lactate (Morel et al., 2015). As expected a mixed task like mauling (components both static and dynamic in nature) was reported to have performance decline with a combination of reduced muscle activation and metabolic alterations.

Both rugby union and rugby league are contact sports, which may alter the development of physiological and perceived fatigue. Johnston and colleagues (2014) investigated the effects of small sided games, involving contact and non-contact on markers of fatigue. Measure of muscular power (countermovement jump and plyometric push-up) were reduced following both the contact and non-contact games, but the reduced power measures were not significantly different from each other (countermovement jump was not reduced more than the plyometric push-up). Blood CK was increased regardless of the intervention, however the peak CK values were different with the contact game resulting in peak values (24 hours following the contact intervention compared to peak values immediately following the non-contact intervention). An additional study by Mullen and colleagues showed increased

session and overall RPE, heart rate, lactate and muscle soreness following a contact rugby league simulation compared to a non-contact simulation. However there were no reductions in strength variables following the game (Mullen et al., 2015). Both of these studies highlight the physical and metabolic demands of the contacts experienced in rugby league and rugby union. Furthermore the effects of the collision can have an effect on how the games are played. That is the interaction between the tasks may have a cumulative effect as contact interventions have reported reduced distance covered (Johnston et al., 2014) and lower peak velocities (Mullen et al., 2015). Furthermore, GPS tracking of match data would suggest that the last five minutes of each half display a reduction in the distance that players (Kempton et al., 2013). Whereas, the first 10 minutes of each half have the highest reported intensities of the matches (Kempton et al., 2015). Moreover, the number of physical collisions is not affected by the period of the game, that is, collisions seem to be even dispersed throughout the game (Kempton et al., 2013; Kempton et al., 2015). These findings show that while movements during a game may change the intensity and amount of collisions remain fairly constant. Therefore, the development of fatigue is largely dependent on the amount and intensity of the collisions experienced by the individuals. It has been reported that the various playing positions experience different levels of physical contact, with forwards experiencing a larger amount than backs. Twist and colleagues showed moderate to strong relationships between the number of collisions and markers of fatigue (psychological, CK and reduced CMJ flight time) in rugby league forwards. However, caution must be enforced when assessing markers of psychophysiological stress as Lindsay and colleagues (2015) showed markers of psychophysiological stress to be independent of playing position.

1.6.4.1 Effects of fatigue on rugby performance

Regardless of the method used to determine the extent of fatigue, the effects of fatigue are seen to manifest during and following a rugby match. The effects of fatigue on the technical performances of the rugby specific tasks related to the studies within this thesis have been investigated and the results are as follows:

- Passing accuracy has yielded inconclusive results regarding the effects of fatigue (Stuart et al., 2005; Hooper et al., 2008)

- Appropriating results from kicking in soccer, it is noted that overall performance, both accuracy (Katis et al., 2013) and velocity (Apriantono et al., 2006) are reduced by fatigue. The reduction stems from changes in the kinetic chain.

- Scrummaging performance (individual) has been reported to be significantly reduced following a repeated sprint effort (Morel et al., 2015) but not following successive scrummaging efforts (Morel and Hautier, 2016).

1.6.4.2 The substitution of fatigued or under-performing players

The reduction in rugby specific performance, as shown above, may be offset by the substitution of fatigued players. Coaches are allowed to make tactical replacements for players they presume are performing less than optimally (Lacome et al., 2016), although there is little quantitative evidence behind the substitution of players. In the modern game the most frequently substituted players are the forwards (Quarrie et al., 2012). Their substituting is most likely due to the high intensity nature of their game requirements, the number of physical collisions they experience and the minimal recovery time between high intensity tasks (Austin et al., 2011). The question as to when to substitute a player can affect the

outcome of the game and is largely based on a subjective evaluation of the coach's previous experiences. Additionally, the introduction of player substitution has changed the way players play and pace themselves during a rugby game (Quarrie and Hopkins, 2007; Higham et al., 2012) as not all fifteen players are required to maintain maximum performance for the entire 80 minutes. The idea of pacing may indirectly affect the development of fatigue within the players.

1.7 Rationale

The physiological demands inherent to the game of rugby are known to vary for different playing positions. Additionally, many skills needed in a competitive rugby team have been specialised to specific playing positions. The players designated as forwards, for example, are required to perform largely static high intensity tasks, while the backs are predominately involved in dynamic movements and high intensity sprints. Despite the non-uniform and varied nature of skills in a rugby team, it is a role of the combination of these different specialised skills, which gives one team an advantage over another. The heterogeneity of these contributions results in difficulties in determining a player's contribution to a team's success or even the individual's level of performance. Assessing athletic performance in rugby through numerous different performance indicators and their interactions is too complex. A systematic approach of identifying technical parameters of individual performance may allow researchers to quantify the parameters that ultimately reflect the performance outcomes. For the purposes of this thesis, and in the context of little preceding work on the field-based measurement of performance in rugby players of different skills, three main factors were identified as tasks indicative of rugby performance. The following three variables were identified as theoretically robust markers of individual rugby performance that culminate in team performance: passing, kicking and scrummaging. The rationale for these variables follows: to effectively pass a rugby ball to another player is a key component of game play, allowing for the cumulative efforts of different players to be made in the territorial progression of a rugby team towards scoring. Passing accuracy was therefore used as the first measure of rugby performance. In the second case, a more accurate kicker is more likely to score points in a rugby game thus kicking accuracy is directly related to rugby scoring potential and therefore is a good indirect measure of rugby performance. In the third case, it is argued that scrummaging success is to a large extent, dependant on one team's

ability to generate more forward momentum than their opposition. This momentum in turn will be dependent on the pushing forces of individuals in a scrum. The third task used to indicate performance was therefore individual scrum force generation.

The study of these selected measures of rugby performance is still relatively novel, and as such there is a limited number of peer reviewed research studies. These studies form the foundation for all further research in the field however many were laboratory based which may have different ecological effects to that which an outdoor rugby environment offers. Advances in technology have also enabled new techniques to be applied to the study of rugby performance. For these reasons, I chose to further the understanding of rugby performance by conducting the studies included in this thesis in the field using modern kinematic and kinetic approaches.

The first two studies (Chapter 2 and 3) will assess the performances of two different passing types. I envisage that by improving the technical nature of the passing strategies, teams may have more accurate passes resulting in greater ball possession during the game. The lack of continuity in the measurement of passing accuracy requires a standardisable approach. Therefore the primary aim of the first study (Chapter 2) is to define a more representative model for passing accuracy. In a similar vein the second study (Chapter 3) will evaluate the performance of the ground pass under two self-selected passing strategies.

Similarly evaluating the potential technical contributors to kicking success could result in the scoring of more points from successful kicks and improved territorial gain. The third study (Chapter 4) will assess the kicking techniques of rugby place-kicking in an attempt to understand the technical determinants of kicking performance. Chapter 5 assesses the potentially different technical approaches to performing the place- and drop-kicks.

Improving scrummaging performance could result in a team physically dominating their opposition. Evaluating the individual scrummaging technique and performance could possibly give teams that desired edge over their opposition. I found it necessary to design and construct a scrummaging ergometer to measure individual scrummaging kinetics (Chapter 6). The construction and validation of the individual scrummaging ergometer lead to the device being applied in a group of competitive 'tight-five' players. The application of such a device may elucidate whether the technical attributes are related to individual scrummaging performance (Chapter 7).

Assessing the effects of fatigue, specifically derived from a match simulation, may allow coaches to more accurately determine when to substitute players contesting in the scrum. Therefore the role that game-induced fatigue may play on the technique and performance of scrummaging ability was assessed. This investigation (Chapter 8) necessitates a standardised match protocol or fatigue intervention. The Bath University Rugby Shuttle Test is one such simulation that can reproduce a rugby union match indoors. Therefore the final study in this thesis assesses the effects of match related fatigue on scrummaging performance.

The findings of this set of studies may assist in the development of approaches of evaluating the individual performances of these rugby specific tasks which could ultimately result in the improvement of team performance. In addition to the gain of a scientific understanding of the nature of these performance related tasks, the findings of the present studies may be useful when directly applied to the training of rugby players.

1.7.1 Objectives

The objectives of this thesis were to:

- Determine and quantify movement variables that predict individual rugby performance.
- Develop an objective measure of passing accuracy (target) based on the definable catching limits of a sample of club rugby players.
- Critically evaluate the differences in passing performance based on self-selected passing technique used during running and ground passing.
- Critically evaluate the kinematic determinants of rugby place kick distance and accuracy on a natural turf outdoor field.
- Compare the kinematic sequences of the place kick and drop kick and their performance outcomes.
- Develop an ergometer capable of determining individual scrummaging kinetics and evaluate positional differences.
- Identify relationships between individual scrummaging technique and individual scrummaging performance.
- Critically evaluate the effects of match related fatigue on scrummaging performance.

Chapter 2:

Rugby union players use different kinematic strategies in the running pass to achieve the same accuracy. Andrew Green, Samantha Kerr, Benita Olivier, Chloe Dafkin and Warrick McKinon. Manuscript currently under review at the *African Journal for Physical, Health Education, Recreation and Dance*.

Abstract

Success in a rugby game is dependent on a team's passing performance, allowing for ball possession to be maintained while a team endeavours to score points. This study kinematically describes the different strategies used by players to perform an accurate running pass on a rugby field. Sixteen university-level players (age 22±2 years; body mass 86.8±16.8 kg) undertook 48 bilateral running passes. Full-body kinematics were analysed for all passes with passing accuracy determined kinematically from 10m. Passes were grouped based on four observed passing strategies: Centre of Mass (COM) raising; COM lowering; in-step; and out-of-step. Passing accuracy was not significantly different between the four different passing strategies (step $p=0.3$, COM $p=0.6$). Greater knee [pass ($p<0.001$); stance ($p=0.001$)] and ankle [pass ($p=0.004$); stance ($p=0.016$)] flexions and a greater head rotation ($p=0.003$) were observed in the COM lowering strategy compared to COM raising. The combined COM movement strategies exhibited greater stance knee flexion ($p=0.002$), larger head rotation ($p=0.002$) and greater lateral bend ($p=0.002$) than the step groups. The out-of-step passes featured larger shoulder ($p<0.001$) and pelvic ($p<0.001$) rotations than the in-step passes and for the combined step groups, passes to the right exhibited greater pelvic rotations ($p=0.017$), lateral bend ($p=0.021$) and head rotations ($p=0.035$). In conclusion, similar accuracy levels were obtained regardless of the passing style used; however different passing approaches may have their own limitations.

Introduction

Passing is a skill that is common to both rugby union and rugby league players. The ability to accomplish an effective pass is essential to the success of a team. The ability to create space by drawing in defenders can result in the attacking team scoring a try. This skill has been named the ‘draw and pass’ and is widely used in rugby league, and to some extent in rugby union. Gabbett, Kelly and Pezet (2008)

The kinematic strategies used to perform the running pass were investigated by Worsfold and Page (2014). They showed that the technique of the players can affect pass velocity and accuracy. Players were divided based on whether they lowered or raised their centre of mass (COM) position prior to the pass. Players who elevated their COM position prior to ball release performed more accurate passes with higher velocities, regardless of the direction of the pass (Worsfold & Page, 2014). Pavely and colleagues (2009) reported a difference in the number of legal passes (lateral or backwards) between the dominant and non-dominant hand. They further report for a single experienced international player that different segmental patterns are used for the preferred and non-preferred sides. This shows that regardless of the playing level of the individual that side dominance is present. These studies have shown how hand dominance and overall technique can affect the passing outcomes, including accuracy.

A second potential technical can be related to the leg around which the pass is performed. The technique promoted by The governing body of rugby union, World Rugby (Online Coaching Manual), and suggests that the player should: place support on their inside leg while decelerating, rotate to face the supporting receiver, identify the target area (chest height slightly in front of the receiver), and use the upper body segments to control the flight (velocity and spin) of the ball. to the authors’ knowledge this is the first study to kinematically investigate the promoted passing technique.

Despite the existence of studies investigating passing accuracy in rugby payers, the measurement of such accuracy measurements has historically been crude (usually a binomial distribution of whether or not a player was able to hit targets of different sizes) and idealistic (based on theoretical notions of what constitutes an accurate pass). The current study aims to identify different strategies used by players to perform an accurate pass while running. Passing accuracy in turn is defined by the reported ideal limits of comfortable catching heights in rugby players and is quantified kinematically at 10m from where the pass originates. In addition, whole body kinematic parameters will be used determine whether technical differences are evident in determining accurate or inaccurate passes from the dominant or non-dominant hand, and to do so on an actual rugby field. It was hypothesised that kinematically different passing strategies with varying degrees of accuracy must be present in different players.

Materials and Methods

Defining the passing accuracy

The accuracy of passing was determined using a custom built target frame. Twenty-seven randomly selected, experienced amateur club rugby players (13 forwards/14 backs. Combined height: 1.83±0.08m) were asked to define what constituted the limits of a catchable pass while running on attack during a game. The rugby players were given a rugby ball to hold and were instructed to place the ball onto a marking surface where comfortable catching limits heights (maximum and minimum) of the ball were recorded. These limits were measured as the maximal and minimal idealised catching height. Maximum height was reported as 1.70±0.20m and minimum catchable height 0.74±0.18m. The averages of these catching limits were used to define the range of a perfect pass within the passing target frame. A passing target (2m×2m) was constructed (Figure 2.1) and placed perpendicularly at 10m from the running direction axis of the players. The middle portion consisted of a rectangular target defined by the vertical limits in-between 0.74m and 1.70m from the ground. The horizontal width of the accurate zone was the length of a regulation rugby union ball (0.33m). In order to quantify passing accuracy for each pass, the position of the central point of the accurate zone was calculated and served as an accuracy reference from which errors in passing accuracy could be compared. To do this, images of passing target frame were recorded using a digital video camera (Sony DCR-SX41, Sony Corporation, Tokyo, Japan) at 30Hz and the position of the ball as it reached the frame was digitally identified using image analysis tools (MatLab 7, Mathworks, Natick, USA). Known positions of the borders of the frame were used to transform pixel coordinates into two dimensional spatial coordinates related to the accuracy frame dimensions and in doing so allowed for the scalar distances between the ball and the central point of the accurate zone (error in passing accuracy) to be determined.

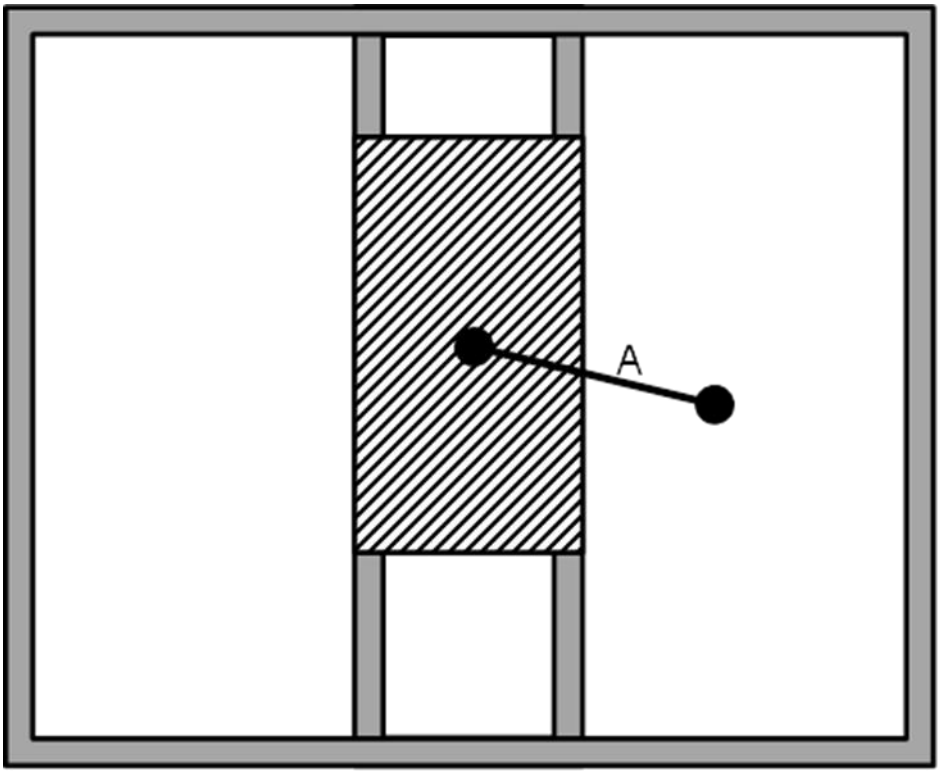


Figure 2.1: Passing accuracy frame (dimensions 2×2m). Shaded area indicates the accurate zone. A. The scalar distance between the position of the ball and the central point of the accurate zone (dimensions 0.96×0.33m).

Participants

Sixteen (eleven backline and five forwards) university level rugby players (age 22±2 years; mass 86.8±16.8 kg; playing experience: 8.7±4.0 years) volunteered to take part in the study. Ethical approval was granted by the University Ethics Committee (clearance number: M131019) and written informed consent was received prior to the start of testing. All participants were right handed and free from injury at the time of the study.

Procedure

Participants underwent a self-guided warm-up prior to testing. To avoid the possibility of potentially refining the passing sequence, participants were limited to a maximum of five practise passes under the experimental conditions. However, all participants were allowed to pass the ball to other players to practice their individual passing sequences. Following this, participants were instructed to aim for a central point of the defined 'accurate area' of 0.31m^2 of the 2×2m target frame. All passes were performed unopposed, running at a self-selected pace similar to that in a match.

All 16 participants performed a total of six passes (three to the left, and three to the right). The order of the passes (towards the left or right) was randomised between participants. A set of standardised training rugby balls (Gilbert XT300, Grays of Cambridge (Int) Ltd, East Sussex, United Kingdom), with regulation inflation were used. No restrictions regarding the passing strategies were enforced. Participants were simply instructed to pass legally towards the target frame (backwards or lateral) with the aim of achieving an accurate pass.

An 18 camera system (Optitrack flex:V100r2, Natural Point Inc., Corvallis, Oregon, USA) encircled a volume large enough to capture the passing sequence on a rugby field at 100Hz. Calibration accuracy was calculated to be sub-millimetre. Calibration and 3D tracking was performed using AMASS (C-Motion Germantown, Maryland, USA). All biomechanical variables were calculated using raw marker trajectories in MatLab 7 (Mathworks, Natick, Massachusetts, USA) with custom written algorithms (described below).

Data reduction

Pass accuracy distance was calculated as the distance between the position of the ball passing through the frame and the known centre of the target. In addition, the binomial description of

the pass was defined as either accurate or inaccurate. Accurate passes were recorded if they hit the limits of the central target area or passed through the central target area. Any passes missing this area were defined as inaccurate.

A total of 96 (48 left and 48 right direction) passes and their respective body kinematics were analysed. A pass to the left was considered to be the dominant side, as the dominant hand has the major controlling action in the sequence. Likewise passes to the right were classified as the non-dominant side. The two main strategies are divided into two main sections. The first strategy was reported by Worsfold and Page (2014), by which players manipulate the position of their COM. The two sub-divisions are classified as COM raising and COM lowering. The COM position was estimated using the position of the sacral retro-reflective marker. The COM position was identified in a static position (individual static kinematic calibration in a T-pose position) and used as a baseline to determine whether the COM position was raised or lowered during the pass sequence. The second classification of pass strategy was based on the stance leg that the player used to rotate around prior to the pass (at ball release). This was objectively determined using the difference between the vectors created at the hips and a vector parallel to the direction of the running motion. Those passing 'out-of-step' would have a hip rotational value of less than 90°. A value of greater than 90° was considered to be an 'in-step' pass (Figure 2). A marker set consisting of 47 retroreflective markers were placed on anatomical landmarks. These were used to create a 15 segment model. The conventional Vicon Plug-In Gait model was used to calculate joint centres (Kadaba et al., 1990; Gutierrez et al., 2003).

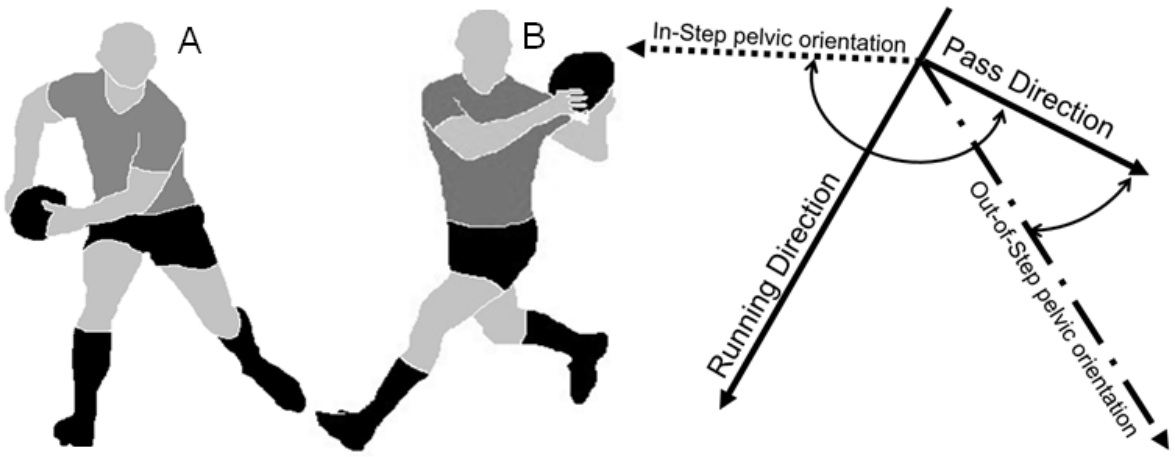


Figure 2.2: The (A) In-Step and (B) Out-of-Step pass as defined by the orientation of the pelvic vector at ball release. (C) Hip rotation vectors viewed from above (*xy* plane) representing the in-step and out-of-step pelvic orientation.

The various kinematic variables (body orientations) were measured and calculated (at ball release) in the following way (Robertson et al., 2004): Neck flexion was calculated as the angle of flexion between the upper thorax and head. Head, shoulder and pelvic rotations were calculated as the difference between the global horizontal vector and the respective body vectors. A rotation value of less than 90° would indicate that the pelvic girdle is orientated with the plant leg leading in the same direction to the running direction. A value larger than 90° would indicate that the pelvic girdle is orientated with the plant leg trailing to the running direction. A description of the pelvic orientation is shown in figure 2.2. X-factor, a variable showing the interaction between the shoulder and pelvic rotations was defined as the difference between shoulder and pelvic rotations. Back flexion was calculated as the angle between the lower back (sacrum to tenth thoracic) vector and upper back (tenth thoracic to seventh cervical) vector. Lateral bend angle was defined as the abduction of the torso plane relative to the pelvic plane. The elbow flexion was calculated bilaterally, as the angle of flexion between the humerus vector and the vector of the forearm. Similarly the wrist angle was calculated bilaterally, as the angle of flexion between the forearm vector and the vector

of the hand. Bilateral knee and ankle flexions were calculated as the angle of flexion between femur vector and the vector of the shank, and the angle of flexion between the vector of the shank and the foot, respectively.

Statistical analysis

All data were tested for normality using a Shapiro-Wilk test. The accuracy distance from centre is represented as median and interquartile range. All remaining data are presented as mean and standard deviation. An unbalanced three-way binomial ANOVA was used to compare the passing outcomes in the two passing groups and hand dominance (COM × Step × Dominance). Two separate unbalanced 3×2 ANOVAs (COM × pass direction × accuracy and Step × pass direction × accuracy) followed by multiple comparison tests were used to determine differences between the kinematics parameters (body orientations) used to execute the running passes. All statistical tests were performed in MatLab 7. An α-value of 0.05 was applied.

Results

Pass accuracy

The accuracy results from the 96 measured passes are reported in Table 2.1. A total of 66 passes were categorised as accurate, with the remaining 30 assigned as inaccurate. There was no significant difference in the passing accuracy for the different passing strategies (COM manipulation compared with step manipulation) used by the participants. The in-step technique was not significantly more accurate than the out-of-step ($p= 0.265$), and neither was the COM lowering more accurate than the COM raising technique ($p= 0.619$). No differences in the passing accuracy were observed between the pass directions, either left or

right (p=0.240). No sizable difference in the proportion of pass type was noted in the COM manipulation techniques however a larger percentage of passes were made using the in-step passing technique regardless of the direction.

Table 2.1: Frequency and distribution of the different strategies used to carry out a running pass

	Centre of Mass Manipulation				Step Manipulation			
	Raise		Lower		In-Step		Out-of-step	
Pass Direction	Left	Right	Left	Right	Left	Right	Left	Right
n	20	27	28	21	31	35	17	13
Directional usage	42	56	58	44	65	73	35	27
Median ± IQR (cm)	28±44	36±87	22±46	33±58	24±52	33±80	21±35	45±50

IQR interquartile range

COM differences

The kinematic variables for the comparison between the COM × pass direction × accuracy are reported in Table 2.2. Greater knee [pass side (p<0.001); stance side (p=0.001)] and ankle [pass side (p=0.004); stance side (p=0.016)] flexions were observed in the COM lowering pass strategy when compared to the COM raising strategy. Similarly a greater degree of head rotation was present in the COM lowering compared to COM raising (p=0.003). A greater degree of stance knee flexion (p=0.002), a larger head rotation (p=0.002) and a greater lateral bend angle (p=0.002) were observed for passes to the right direction. A larger lateral bend angle was present in accurate passes compared to the inaccurate passes (p=0.047).

Step differences

Step × pass direction × accuracy comparison for the kinematic variables are reported in Table 2.3. Larger rotations of the shoulder (p<0.001) and the pelvic (p<0.001) girdles were observed between the out-of-step and in-step passes. Greater pelvic rotations (p=0.017),

lateral bend (p=0.021) and head rotations (p=0.035) were present when passes were made towards the right (non-dominant side). A larger lateral bend angle was used when accurate passes were made compared to inaccurate passes (p=0.018).

Discussion

The current study has identified various strategies used to execute a running pass in rugby. While no differences in the accuracy was found between the passing styles (COM manipulation and step manipulation), the study does recognise the differences in the body kinematics used to accomplish the passes. The results indicated that a high level of passing accuracy is maintained regardless of the passing strategies used by players. Notwithstanding the lack of accuracy differences between passing strategies, when the kinematics of each passing type were analysed, a possible role of a greater lateral bend angle in contribution to accurate passing was identified. The lateral bend angle is a description of the adduction angle between the pelvis and torso. The latter finding however was evident despite the fact that players with lower COM strategies did not necessarily pass more accurately.

Table 2.2: The kinematic variables (body orientations) for the grouped comparisons of the Centre of Mass manipulation strategy

	Lower COM				Raise COM			
Pass direction	Left		Right		Left		Right	
Angle (°)	accurate	inaccurate	accurate	inaccurate	accurate	inaccurate	accurate	inaccurate
Neck flexion	95.7±18.9	108.3±7.0	96.3±11.0	89.5±13.6	96.7±11.8	95.8±8.3	95.8±8.1	95.1±10.4
Shoulder rotation	65.4±72.0	40.7±50.8	34.0±40.1	72.5±76.6	82.0±57.5	35.0±39.0	79.6±55.3	72.1±59.5
Pass elbow flexion	69.7±16.3	65.7±4.9	74.2±8.7	69.8±14.1	69.8±9.8	83.0±11.6	69.8±13.3	74.2±20.5
Stance elbow flexion	57.2±22.3	53.3±16.1	50.9±7.9	49.0±11.0	49.6±14.3	46.2±8.1	42.6±13.8	48.0±27.5
Pass wrist flexion	154.7±7.5	146.1±3.1	139.1±35.1	146.4±19.2	141.8±21.8	155.9±1.8	155.4±18.2	124.5±41.4
Stance wrist flexion	130.7±16.2	124.3±16.7	129.2±10.7	122.8±13.0	128.6±19.1	135.0±16.6	125.8±27.7	134.2±15.7
Pelvic rotation	73.3±65.6	39.4±48.4	47.9±41.7	77.6±71.6	78.1±54.9	43.3±45.0	76.6±48.6	75.3±53.1
X-Factor	-7.9 +11.3	1.3±4.8	-13.9±11.2	-5.0±6.8	3.9±37.4	-8.3±14.5	3.0±14.2	-3.3±9.5
Pass knee flexion*	70.4±32.9	95.1±19.0	72.4±32.0	74.0±35.8	58.5±17.1	52.8±21.2	56.6±25.5	47.2±10.2
Stance knee flexion*†	66.7±39.2	75.5±39.6	101.4±29.1	95.4+-35.7	65.0±30.1	43.2±29.8	67.3±31.2	58.7±34.3
Pass ankle flexion*	86.5±13.7	97.4±23.3	77.2±10.4	92.0±20.0	72.6±10.4	75.6±3.1	81.6±15.6	77.3±14.8
Stance ankle flexion*	76.3±18.9	70.1±13.2	85.2+-20	74.3+-13.3	74.6±13.6	64.7±21.9	65.5±11.0	64.4±12.8
Lateral bend†#	13.6±4.9	9.7±3.4	20.1±9.1	14.4±9.2	14.9±5.7	12.2±6.3	18.6±7.5	17.9±6.8
Head rotation*†	90.1±6.3	88.2±3.1	94.7±2.4	92.6±4.0	84.7±6.5	83.0±7.8	86.7±9.1	93.2±8.2
Back flexion	14.4±3.5	11.9±11.6	21.5±8.5	21.6±4.5	22.3±11.3	16.6±10.6	17.0±5.2	28.8±27.9

* significant difference between COM type ($p<0.05$)
† significant difference between pass direction ($p<0.05$)
#significant difference accurate and inaccurate ($p<0.05$)

Table 2.3: The kinematic variables (body orientations) for the grouped comparisons of the Step manipulation strategy.

	Out-of-step				In-Step			
Pass Direction	Left		Right		Left		Right	
Angle (°)	accurate	inaccurate	accurate	inaccurate	accurate	inaccurate	accurate	inaccurate
Neck flexion	95.4±13.8	95.0±5.1	98.2±9.3	92.1±13.5	96.7±17.5	104.3±9.9	95.1±8.9	92.8±11.7
Shoulder rotation*	139.8±33.5	129.0±36.0	142.8±38.1	159.7±10.0	24.1±31.3	20.2±8.2	34.6±23.3	28.6±18.1
Pass elbow flexion	68.6±11.4	69.7±7.2	70.4±10.2	77.5±18.7	70.5±15.9	71.0±12.3	71.9±12.4	67.8±16.2
Stance elbow flexion	51.0±11.3	51.3±7.2	46.0±7.4	69.1±32.3	55.3±22.7	50.2±14.9	47.3±13.0	41.5±12.3
Pass wrist flexion	142.8±19.6	144.4±1.2	155.2±16.4	118.2±38.9	155.6±8.7	150.0±5.5	146.3±30.0	148.4±22.3
Stance wrist flexion	132.1±18.8	130.2±10.9	138.6±16.3	122.9±10.2	128.2±17.0	128.5±18.2	124.1±23.4	131.3±17.1
Pelvic rotation*†	142.1±27.5	133.2±21.9	140.9±25.1	156.0±11.8	27.6±13.1	22.6±12.2	40.8±18.0	36.5±17.7
X-Factor	-2.3±9.1	-4.3±14.2	1.9±17.5	3.7±7.4	-3.5±33.3	-2.4±10.7	-6.2±14.5	-7.9±5.6
Pass knee flexion	66.9±24.7	86.4±26.9	60.4±23.6	59.4±22.0	64.1±29.7	81.4±29.4	64.4±31.0	56.5±27.9
Stance knee flexion	58.8±35.4	37.4±35.5	78.6±36.2	78.4±30.1	70.8±35.0	66.9±38.4	82.7±35.9	72.8±41.7
Pass ankle flexion	78.6±15.3	86.6±17.4	89.4±11.4	93.3±18.8	81.5±13.4	91.9±23.7	76.9±13.4	77.4±12.1
Stance ankle flexion	77.9±21.1	65.5±7.1	80.2±5.3	76.9±10.3	73.7±11.8	68.3±18.2	72.8±19.4	65.4±13.4
Lateral bend†#	15.5±5.5	15.2±3.3	23.4±11.5	8.0±6.8	13.2±5.0	9.8±4.6	18.3±7.2	20.5±4.2
Head rotation†	88.0±9.5	84.2±14.4	88.6±4.0	87.8±1.8	87.7±4.6	86.4±4.3	90.6±8.9	95.5±6.5
Back flexion	20.6±10.2	13.1±5.1	18.4±9.0	18.1±4.3	15.6±6.5	14.2±12.0	19.0±7.0	28.5±23.6

* significant difference between Step type ($p<0.05$)
† significant difference between pass direction ($p<0.05$)
#significant difference between accuracy ($p<0.05$)

Passing type and direction

There were no significant differences in the pass accuracy between the passing types. This may be a result of the small target area used. The accuracy target was defined as an area of 0.31m^2 placed within a 2×2m frame. This accuracy area is relatively small compared with other investigations into passing accuracy (Stuart et al., 2005; Hooper et al., 2008; Assi and Bottoms, 2014; Worsfold and Page, 2014;). For a pass to simply strike an area defined as catchable does not reflect the true nature of the pass accuracy. The limits of the accurate zone in the current study were defined by a group of amateur players and this reflects the catching ability of the ball receiver. This is especially true when it came to the height of the pass. However Gabbett et al. (2008) suggested that a pass should be made ahead of the intended target. This is to allow the advancing player to maintain their forward momentum while attempting to catch the ball. This in conjunction with the physical limits set by the target player should be the constraining factor of an accurate pass. Another variable that may affect the accuracy of the pass may be the distance over which the accuracy was tested, distances varying from 4m (Stuart et al., 2008) to 12m (Worsfold and Page, 2014) have been studied. In the current study a player-target distance of 10m was chosen to still be representative of the type of passes found in a game but was closer to the larger extreme of those distances previously tested, in order to maximise the sensitivity of measurements of passing accuracy. Moreover there was no evidence to suggest that the hand dominance affected the pass accuracy. This lack of dominance effect is a surprising finding as multiple studies have reported the pass towards the dominant side to be more accurate than the non-dominant side (Pavely et al., 2009; Worsfold and Page, 2014). One possible explanation for the similarities in the accuracy for passing direction in this study may be that the players use a completely different passing strategy when passing to the dominant side compared to that that they use for the non-dominant side.

COM raising vs lowering

The COM manipulation passing technique shows how players either elevate or lower their whole body COM position during the passing sequence. The COM lowering passing technique may be beneficial to players in the sense of creating a firmer centre of support closer to the ground. The results of the current study suggested that the players created this base lower to the ground using a greater bilateral flexion of the knees and ankles. This result is similar to the Worsfold and Page (2014) study, which found that players in the body drop group (comparable with the COM lowering) widened their base of support, flexed their knees and trunk, which lowered their COM position. The consequences of these kinematic changes should improve the player's stability. While the body drop technique required the height of the player to lower, all passes were made (ball release) when the trunk and knees were extending. Moreover a lower body position resulted in more accurate passes (Worsfold and Page, 2014) This finding may reflect that power generation for passing with a low COM strategy may originate in the lower body, and the reduction in height may be a side-effect of slowing down to perform the pass.

The COM raising technique in the current study is comparable with the non-body drop technique from Worsfold and Page (2014). Worsfold and Page (2014) suggested that the COM raising technique requires more input from the arms to generate the energy. They continued to comment qualitatively that stability was compromised during the COM raising technique and the lower limbs had to counter-balance the momentum of the arm following ball release (Worsfold and Page, 2014).

No significant differences in passing accuracy were noted in the current study when the passes were grouped based on the position of the COM. This finding is contrary to the findings of Worsfold and Page (2014) who reported more accurate passes were made in the

COM lowering strategy. This may be a result of the determining factors by which the group divisions occurred. The current study estimated the COM position at ball release, whereas Worsfold and Page (2014) in their body drop group measured the height difference during the pass sequence. The height difference would be affected by multiple variables (neck flexion, back flexion, and lower limb flexion). By measuring the COM position, instead of change in height, these variables which may affect the passing outcomes are less likely to become defining features and the division less prone to error.

Passing while in-step compared with out-of-step

The objective criterion of the step pass classification resulted in the larger rotations of the shoulder and pelvic girdles in the out-of-step passes. The rotation of the pelvis indicated that the passes were made off the incorrect stance leg. Coaching manuals (World Rugby Coaching Website) suggest that the stance leg should be that opposite to the direction of the pass (a pass to the left direction would have the right leg as the supporting stance leg). Additionally a pass to the left should have the right leg planted and the pelvis and shoulders should rotate towards the receiving player. The support leg should act as a pivot around which the girdles can rotate. This sequence shouldn't interfere with the gait cycle as the momentum used to slow down the player would be transferred to the rotational energy of the girdles, upper-body segments and eventually the ball. The opposite should be true for the out-of-step passes. By planting the leg on the same side as the pass, it is expected that the player would have to exaggerate their body rotations to achieve the same level of ball velocity. For these reasons, out-of-step passing is not considered to be an energy efficient strategy to transfer optimal energy to the ball. Despite this, data from the present study show that such passes do not compromise passing accuracy.

Running speed and ball carrying capabilities

Pavely et al. (2009) suggested that the passing accuracy discrepancies, between the side to which the pass was executed, present in their study may be attributed to the changes in motor control of the gait cycle. While no accuracy differences were present between the passing styles (COM manipulation or step manipulation) or pass direction, in the current study the idea that a mismatch in the motor control during the gait cycle may be important. Irrespective of the step passing strategy used, larger pelvic rotations were reported for passes directed to the right. This may be a direct result of this mismatch or may be a strategy to ensure an accurate pass and the coordination of the segments when passing to the non-dominant side.

The step type may be influenced by the running speed during the approach to the passing area. The degree of pelvis rotation is reliant on the speed of locomotion and acts differently when walking or running (Schache et al., 2002). The pelvis may be externally rotated, and open to the target, when the stance leg is planted depending on the speed at which the player is running. If this were the case, then the plant leg would be on the same side as the pass direction.

Running speed has been shown to be reduced when the ball is carried in both hands compared to a single side (Grant et al., 2003). This running speed difference was independent of the experience of the rugby player (Walsh et al., 2007). Furthermore carrying the ball in both hands was shown to reduce players' abilities to perform agility tests (Meir et al., 2014). In all cases the underlying mechanism for the reduction in running performance is attributed to the restriction of the upper body segments thereby reducing their ability to counter the momentum of the lower body (Grant et al., 2003; Walsh et al., 2007; Meir et al., 2014). Further investigations are required to investigate the relationships between running speed and pass accuracy.

One reason why a player may select the in-step passing style is to draw in a defender. Gabbett, Wake and Abernathy (2011) reported the criteria for the draw-and-pass skill used widely in rugby league. Two of the seven criteria are displayed by the players when executing the in-step pass, namely to: have their body square with the defender; and to pass in the opposite direction to the leading or stance leg (Gabbett, Wake & Abernathy 2011). These skills can potentially be used in rugby union to draw in the defender in an attempt to create space for the supporting player. Gabbett and Abernathy (2012) showed how nearly half of all tries scored in a season of Rugby League were scored by players using the draw-and-pass technique. Such beneficial strategies are likely trained into players and individual variations of this technique are developed based on the players' physical capabilities. While certain strategies may lead to scoring opportunities, others may result in adverse situations during a game. The body drop technique took longer to execute, when compared to passes that did not utilise the body drop technique (Worsfold and Page 2014).

Hand dominance and pass accuracy

A larger head rotation was observed when passes were made to the non-dominant side (right). This finding is in agreement with Pavely et al. (2009) who reported that players exhibited a more pronounced head rotation when passing to the non-dominant side. The larger head rotations were observed in both the COM and step groups in the current study. This highlights the importance of identifying the target prior to the commencement of the pass sequence. This may be exaggerated when passing to the non-dominant side. The only other kinematic variable that was different between the dominant and non-dominant side passes was the larger lateral bend angle to the non-dominant side.

Worsfold and Page (2014) reported that the body drop technique was used more often on the non-dominant side and more frequently as pass distance increased indicating that players

must use different strategies to maintain accuracy in passes of varying distance. No sizable differences in the amount of passes (type vs direction) are noted in the current study. Although more passes were made in the in-step style compared to the out-of-step, this was irrespective of the direction of the pass however.

In both the COM and step groups the only distinguishing factor between an accurate and inaccurate pass was the degree of lateral bend. A larger lateral bend angle was associated with an accurate pass. The lateral bend angle may be affected by the running cycle in conjunction with the passing sequence, and warrants further investigation, specifically as running velocities change and such changes may influence pass velocity.

Limitations

The sample used in the current study only represents a small group of rugby players. There are known anthropometrical differences between the playing positions (Duthie & Hooper, 2003; Quarrie and Hopkins, 2007) (forwards and backs). Additionally Gabbett et al. (2008) observed differences in passing ratings based on subjective coaching between three positional groups in rugby league players. Further research into the passing approaches and accuracy outcomes should be encouraged. Additionally the passing strategies used in a live game have yet to be reported.

Methodologically passes were performed unopposed, which may not reflect match situations, player may accordingly change their approach to the pass and the pass accuracy may be affected by the inclusion of opposition. Additionally, more complex modelling of the passing sequence is warranted, with respect to cardan sequencing of the torso, arms and hands.

The result from the current study may not be applicable to an elite playing sample. While variations in the passing techniques, with regard to their accuracy, were evident in the current

study; similar finding may not be present in elite players. Higher level players may have technical variations to their passing sequence, but may attain a level of passing accuracy, regardless of their technique. Further research into the technical variation of more elite groups is required to definitively answer this question.

Conclusion

While no differences in the pass accuracy were found, the study identified four different approaches to passing, namely: COM raising; COM lowering; ball release in-step; and ball release out-of-step. These passing approaches may have their own advantages and disadvantages when used during a match, but the passing accuracy outcomes would suggest that regardless of the passing style used, all passes were accomplished to a similar level of accuracy.

Practical applications:

While no accuracy differences were observed between the two investigated strategies (STEP or COM), player may choose to select a technique that is tailored to their physical limits.

Technical variation may be encouraged as the major concern should be related to the outcome of the pass and not the technique used to execute the pass.

A strategy should be selected that does not impede running speed, place the player at unnecessary risk of injury or have a negative effect on performance.

References

Assi, H.N. & Bottoms, L. (2014). The effects of caffeine on rugby passing accuracy while performing the Reactive Agility Test. *Science & Sports*, 29(5): 275-281.

Duthie, G., Pyne, D. & Hooper, S. (2003). Applied Physiology and Game Analysis of Rugby Union. *Sports Medicine*, 33(13): 973-991.

Gabbett, T. & Abernathy, B. (2012). Dual-task assessment of a sporting skill: influence of task complexity and relationship with competitive performances. *Journal of Sports Sciences*, 30(16): 1735-1745.

Gabbett, T., Kelly, J. & Pezet, T.A (2008). Comparison of fitness and skill among playing positions in sub-elite rugby league players. *Journal of Science and Medicine in Sports*, 11(6): 585-592.

Gabbett, T., Wake, M. & Abernathy, B. (2011). Use of dual-task methodology for skill assessment and development: Examples from rugby league. *Journal of Sports Sciences*, 29(1): 7-18.

Grant, S.J., Oommen, G., McColl, G., Taylor, J., Watkins, L., Friel, N., Watt, I. & McLean, D. (2003). The effects of ball carrying method on sprint speed in rugby union football players. *Journal of Sports Sciences*, 21(12): 1009-1015.

Gutierrez, E.M., Bartonek, A., Haglund-Akerlind, Y. & Saraste, H. (2003). Centre of mass motion during gait in persons with myelomeningocele. *Gait and Posture*, 18(2): 37-46.

Hooper, J.J., James, S.D., Jones, D.C., Lee, D.M. & Gál, J.M. (2008). The influence of training with heavy rugby balls on selected spin pass variables in youth rugby union players. *Journal of Science and Medicine in Sport*, 11(2): 209-213.

Kadaba, M.P., Ramakrishnan, H.K. & Wooten, M.E. (1990). Lower extremity kinematics during level walking. *Journal of Orthopaedic Research,* 8(3): 849-860.

Meir, R., Holding, R. & Hetherington, J. (2014). Impact of the two-handed rugby ball carry on change of direction speed and reactive agility: implications for sport specific testing. *International Journal of Sports Science and Coaching*, 9(5): 1181-1190.

Pavely, S., Adams, R.D., Di Francesco, T.I., Larkham, S. & Maher, C.G. (2009). Execution and outcome differences between passes to the left and right made by first-grade rugby union players. *Physical Therapy in Sport*, 10(4): 136-141.

Quarrie, K.L. & Hopkins, W.G. (2007). Changes in player characteristics and match activities in Bledisloe Cup rugby union from 1972 to 2004. *Journal of Sports Sciences*, 25(8): 895-903.

Robertson, D.G.E., Caldwell, G.E., Hamill, J., Kamen, G. & Whittlesey, S.N. (2004). Research Methods in Biomechanics. Human Kinetics.

Schache, A.G., Bennell, K.L., Blanch, P.D. & Wrigley, T.V. (1999). The coordinated movement of the lumbo–pelvic–hip complex during running: a literature review. *Gait & Posture*, 10(1): 30–47.

Schache, A.G., Blanch, P., Rath, D., Wrigley, T. & Bennell, K. (2002). Three-dimensional angular kinematics of the lumbar spine and pelvis during running. *Human Movement Science*, 21(2): 273–293.

Stuart, G.R., Hopkins, W.G., Cook, C. & Cairns, S.P. (2005). Multiple effects of caffeine on simulated high-intensity team-sport performance. *Medicine & Science in Sports & Exercise*, 37(11): 1998–2005.

Walsh, M., Young, B., Hill, B., Kittredge, K. & Horn, T. (2007). The effect of ball-carrying technique and experience on sprinting in rugby union. *Journal of Sports Sciences*, 25(2): 185-192.

World Rugby Coaching Website. http://coaching.worldrugby.org/?module=1&section=1&subsection=1. Accessed 23/09/2015

Worsfold, P.R. & Page, M. (2014). The influences of rugby spin pass technique on movement time, ball velocity and passing accuracy. *International Journal of Performance Analysis in Sport*, 14(1): 296-306.

Chapter 3:

Rugby ground passes: A side-on body orientation is more accurate than front-on body orientation. Andrew Green, Samantha Kerr, Benita Olivier, Chloe Dafkin and Warrick McKinon. Manuscript submitted the *South African Journal of Sports Medicine.*

Abstract

One of the crucial components of a team's success in rugby is the pass. The passing component within rugby has gone largely understudied. This study identifies biomechanical correlates of the rugby ground pass and accuracy performance. Sixteen club players (height 1.77±0.04m; mass 86.8±16.8kg) undertook a combined total of 96 passes and their respective body kinematics were analysed concurrent with measurements of pass accuracy at 10m. Two distinct types of body orientations were utilised by the players; a side-on orientation (pelvic rotation angle of >80°) and a front-on orientation (pelvic rotation angle <80°). Side-on body orientation passes were more accurate than front-on body orientation passes ($p<0.0001$). Fair relationships were present between the pass accuracy and body kinematics for the two distinct body orientations. However no common relationships were observed between the different orientations. Therefore different strategies exist within players to perform the ground pass with varying grades of accuracy.

Background

All rugby players are required to be proficient at passing the ball, unlike the specialist areas distinct to rugby (scrum and lineout), however variation in passing ability among playing positions has been reported (Gabbett et al., 2008). Current research has highlighted the effect of hand dominance on the rugby pass, both maximally (Pavely et al., 2009) and over various set distances (Worsfold & Page, 2014). Recent studies have shown that training is known to influence passing dynamics (Hooper et al., 2008) and that caffeine supplementation does not influence passing accuracy (Assi & Bottoms, 2014). Interestingly these studies have looked exclusively at the running pass. Another passing type in rugby is the pass from the ground. When a scrum or breakdown occurs the ball will be placed on the ground where the arriving player will attempt to distribute the ball to another advancing player. The ground pass is made from a comparatively static position, when compared to the running pass.

Currently there is only one study that has investigated the ground pass in rugby conducted by Sayers and Ballon (2011). This study assessed the kinematic of the upper body during the ground pass, and reported significant correlations between shoulder velocities and pass velocity (Sayers and Ballon, 2011). While Sayers and Ballon (2011) reported higher accuracy scores for the preferred side pass than the no preferred side, kinematic variables were related to the achieved accuracy.

The whole body kinematic evaluation of the ground pass is limited and performance parameter surrounding the ground pass are largely unknown, specifically with respect to the pass accuracy. The purpose of this study was therefore to primarily assess whether biomechanical correlates of the rugby ground pass accuracy exist in high level amateur rugby players. It was hypothesised that passing accuracy may be related to the upper body

kinematics of the players, specifically the rotations of the torso and pelvic girdles along with additional contributions from the arm segments.

Methods

Participants

The sixteen first team university level rugby players that volunteered for this study had an average age of 22±2 years; height of 1.77±0.04m and body mass of 86.8±16.8kg. Ethical approval was granted by the University Ethics Committee (M131019) and written informed consent was received prior to the start of testing. All participants were right handed and injury free at the time of the study.

The participants were required to pass from a distance of 10m towards a target. The frame consisted of a 2m×2m metal frame with a middle portion consisting of a rectangular target defined by the vertical limits in-between 0.74m and 1.77m from the ground. The horizontal width of the target was the length of a regulation rugby union ball (0.33m). The vertical limits were based on data collected from 27 players, when asked what constituted the limits of a catchable pass while running on attack during a game. Pass accuracy was quantified as the distance of the ball position from the central point of the accurate zone. Digital video images were recorded (Sony DCR-SX41, Sony Corporation, Tokyo, Japan) and the position of the ball as it reached the frame was digitally identified using image analysis tools (MatLab 7, Mathworks, Natick, USA).

Full-body kinematics were recorded using an 18 camera system recording at 100 Hz (Optitrack flex:V100r2, Natural Point Inc., Corvallis, Oregon, USA). A measurement volume of approximately 32m^3 was calibrated (AMASS, C-Motion Germantown, Maryland, USA) in the area where ball release would occur, to a level of sub-millimetre error. Custom written

algorithms were used to analyse body positions as derived from raw marker location data in MatLab 7.

The various kinematic variables were measured and calculated in the following way: Neck flexion was calculated as the angle of flexion between the upper thorax and head. Head, torso and pelvic rotations were calculated as the difference between the global horizontal vector and the respective body vectors. A rotation value of less than 80° would indicate an open stance with the body facing the target. A value larger than 80° would indicate that the body would be parallel to the target direction. X-factor was defined as the difference between torso and pelvic rotations. Back flexion was calculated as the angle between the lower back (sacrum to tenth thoracic) vector and upper back (tenth thoracic to seventh cervical) vector. Lateral bend angle was defined as the abduction of the torso sagittal plane relative to the pelvic sagittal plane. The elbow flexion was calculated bilaterally, as the angle of flexion between the humerus vector and the vector of the forearm. Similarly the wrist angle was calculated bilaterally, as the angle of flexion between the forearm vector and the vector of the hand. Bilateral knee and ankle flexions were calculated as the angle of flexion between femur vector and the vector of the shank, and the angle of flexion between the vector of the shank and the foot, respectively.

The passing kinematics were analysed at the moment of ball release. Two distinct passing groups were identified: one group with a pelvic rotation angle of greater than 80° between the direction of the target and the pelvic vector (side-on orientation) and one with a pelvic rotation angle of less than 80° between the direction of the target and the pelvic vector (front-on orientation).

Procedure

Participants underwent a self-guided warm-up prior to testing. All participants were allowed no more than five practise passes under the experimental conditions. All participants performed in a randomised order a total of six passes (three to the left, and three to the right) using a set of standardised training rugby balls (Gilbert XT300, Grays of Cambridge (Int) Ltd, East Sussex, United Kingdom). Participants were instructed to pass legally (backwards or lateral) towards the target with the aim of achieving an accurate pass.

Statistical analysis

All data distributions were analysed using a Shapiro Wilk normality test. Passing accuracy error distance did not conform to a normal distribution and is represented as median±inter-quartile range. A Mann-Whitney test was used to compare accuracy differences between the two passing orientation types. All kinematic data are represented as mean±standard deviation. Spearman's correlations were performed between the pass accuracy error distance and the kinematic variables at ball release in MatLab 7. A significance level of $p<0.05$ was applied.

Results

The passing accuracy error was not significantly ($p=0.945$) different between the right direction (20.0 cm: 8.4-44.9cm) and the left direction (20.9 cm: 9.1-43.8cm). The pass accuracy error distances were significantly larger ($p<0.0001$) for the front-on body orientation (34.1 cm: 12.9-49.1 cm) (n=64) compared to the side orientation 8.8 cm: 4.4-20.3 cm) (n=32). Correlations between body kinematics and the pass accuracy distances, and their qualitative descriptions, are reported in Table 3.1.

Negative correlations were present for the pass side elbow flexion and X-Factor in the front-on orientation and pass accuracy error. For the side-on orientation negative correlations were

observed between neck flexion, stance side wrist flexion and pass side wrist flexion and pass accuracy error.

Positive correlations were present for head rotation in the front on orientation and pass accuracy error. In the side on orientation stance side elbow flexion was positively correlated to pass accuracy error.

Discussion

Unlike previous studies that investigated the running pass in rugby players (Gabbett et al., 2008; Hooper et al., 2008; Pavely et al., 2009; Assi & Bottoms, 2014; Worsfold & Page, 2014), the current study aimed to kinematic strategies and accuracy performance of the rugby ground pass. It was noted that two distinct types of body orientations were utilised by the players. These two distinct types of body orientations resulted in differences in accuracy performance and kinematic correlations.

Table 3.1: Kinematic joint angular data and Spearman's rank correlation coefficients for kinematic variables and their relationships to the pass accuracy error distance for front and side body orientations.

	Front body orientation (n=64)			Side body orientation (n=32)		
	Kinematic angle (°)	Spearman's r	Qualitative descriptions†	Kinematic angle (°)	Spearman's r	Qualitative descriptions†
Neck flexion	100.2±13.4	0.124	little	99.3±15.6	**-0.458***	fair
Head rotation	88.4±9.5	**0.382***	fair	88.6±7.4	-0.154	little
Torso rotation	32.4±18.6	-0.189	little	143.1±39.4	0.122	little
Lateral Bend	15.9±8.1	0.002	little	16.9±7.9	0.269	fair
Back Flexion	15.7±8.2	0.204	little	17.9±4.0	-0.027	little
Stance side elbow	68.1±18.7	-0.258	fair	66.0±15.3	**0.655***	moderate
Pass side elbow	50.2±17.6	**-0.331***	fair	52.9±12.6	0.013	little
Stance side wrist	149.1±15.6	-0.21	little	150.0±13.0	**-0.457***	fair
Pass side wrist	127.2±22.7	0.134	little	130.6±17.8	**-0.464***	fair
Pelvic rotation	35.8±14.6	-0.105	little	133.8±33.2	-0.182	little
X-Factor	-2.7±12.7	**-0.380***	fair	6.7±14.8	0.14	little
Stance side knee	58.1±27.5	0.05	little	57.0±19.9	-0.255	fair
Pass side knee	53.6±28.3	0.055	little	53.5±24.0	-0.095	little
Stance side ankle	75.2±16.4	0.096	little	81.4±19.1	0.253	fair
Pass side ankle	65.4±8.8	0.111	little	64.5±6.0	-0.118	little

† Qualitative descriptions for the strength of the relationships were defined as Portney and Watkins (2009): r=0.00-0.25 little or no relationship; r=0.25-0.50 fair relationship; r=0.50-0.75 moderate to good relationship; r>0.75 good to excellent relationship.

* $p<0.05$ Spearman's rank correlation coefficient

The significant correlations highlight interesting relationships between the body movements and pass accuracy independent of the two distinct body orientations. Isolating the front-on body orientation the positive correlation for accuracy and head rotation would suggest the importance of identifying the target in executing an accurate pass. Furthermore the front-on body orientation requires a greater extension of the pass side elbow, while in the side-on body orientation requires the stance elbow flexion to be larger to achieve accurate passes. A significant correlation between the velocity of the stance side elbow flexion and the resulting pass velocity has been reported (Sayers & Ballon, 2011). Consequently the stance side elbow may be essential to the performance of the pass. Interestingly the passes were more accurate with decreasing values of X-Factor. This would suggest a greater torso rotation relative to the pelvic rotation is needed to achieve an accurate pass.

Front-on orientation compare with handballing in Australian Football (Parrington et al., 2014). Their regression analysis showed significant inclusion of trunk-pelvis separation (at the point when the hand makes contact with the ball). Furthermore, the separation angle (analogous to X-Factor in the current study) was significantly related to the hand velocity. This inclusion may add value to the significant relationship with the variable X-Factor in the current study. importance of the kinetic chain in the development and transfer of velocity between segments.

Regarding the side-on body orientation relationships: pass accuracy requires more neck flexion and bilateral wrist flexion, as indicated by the significant correlations. These results may indicate that in this body orientation, the players would need to elevate their heads to observe and identify the target by reducing the degree of neck flexion.

The relationships shown for the pass accuracy and the different body orientations highlight the potentially different strategies that are used to achieve and accurate pass. Interestingly

there were no common kinematic variables that were significantly correlated to accuracy between the two different body orientations. It would appear that in the side-on orientation that the players would rely on the arms, specifically the stance elbow flexion head flexion, stance side wrist flexion and pass side wrist flexion. While the front-on body orientation utilises head rotation, pass side elbow flexion and X-Factor (torso and pelvic girdle separation) to achieve accurate passes.

Important relationships between the velocities of the shoulder motions and the pass velocity (Sayers and Ballon, 2011). However no relationships were reported between the upper body kinematics and pass accuracy.

While these relationships do give some insight into the different strategies used in the two distinct pass styles they do not definitively identify all the parameters used by the players. Furthermore the significant correlations merely identify fair relationships between the parameters and do not imply causation. Further investigation, specifically into the muscular activity, is required to conclusively answer this. Ultimately the passing type used by the players should not affect the game-play provided they are able to achieve an accurate pass. The data within the current study would suggest that the side-on pass orientation was shown to be more accurate than the front-on pass. However the accuracy constraints in the current study do not take into account any movement of the receiving player, with the vast majority of passes likely to be caught by the receiving player. Additional limitations include: the small sample size; playing level of the participants; and the limited number of passes performed by each player. Future studies are warranted to investigate the duration of the passes and the effects of playing position on the body orientations used to perform the passes.

Conclusion

The current study has identified two different kinematic passing strategies used by players to achieve different levels of pass accuracy. Specifically, the side-on body orientation produced more accurate passes than the front-on body orientation. Coaches should train ground passing strategies that result in the most accurate outcomes. The majority of ground passes performed by a sample of rugby players of various positions resulted in a front-on body orientation. However, when a side-on pass orientation was used, the passes were significantly more accurate. Passing strategies may be reliant on the orientation of the body relative to the target.

References

Assi, H.N. & Bottoms, L. (2014). The effects of caffeine on rugby passing accuracy while performing the Reactive Agility Test. *Science & Sports*, 29: 275-281.

Gabbett, T., Kelly, J. & Pezet, T.A (2008). Comparison of fitness and skill among playing positions in sub-elite rugby league players. *Journal of Science and Medicine in Sports*, 11(6): 585-592.

Hooper, J.J., James, S.D., Jones, D.C., Lee, D.M. & Gál, J.M. (2008). The influence of training with heavy rugby balls on selected spin pass variables in youth rugby union players. *Journal of Science and Medicine in Sport*, 11: 209-213.

Parrington, L., Ball, K. & MacMahon, C. (2014) Biomechanical characteristics of handballing maximally in Australian football. *Sports Biomechanics*, 13(4): 307-319.

Pavely, S., Adams, R.D., Di Francesco, T.I., Larkham, S. & Maher, C.G. (2009). Execution and outcome differences between passes to the left and right made by first-grade rugby union players. *Physical Therapy in Sport*, 10(4): 136-141.

Portney, L.G. & Watkins, M.P. (2009). Foundations of Clinical Research: Applications to Practice (Third Edition ed.). London: Pearson Prentice Hall.

Sayers, M. & Ballon, R. (2011). Biomechanical analysis of a rugby pass from the ground. 7th World Congress of Science and Football, Nagoya, Japan 26-30 May 2011.

Worsfold, P.R. & Page, M. (2014). The influences of rugby spin pass technique on movement time, ball velocity and passing accuracy. *International Journal of Performance Analysis in Sport*, 14(1): 296-306.

Chapter 4:

The trade-off between distance and accuracy in the rugby union place kick: a cross-sectional, descriptive study. Andrew Green, Samantha Kerr, Benita Olivier, Chloe Dafkin, and Warrick McKinon. Manuscript accepted for publication in the journal *Kinesiology.*

Abstract

Little attention has been given to the rotational kinematics of rugby union place kicking performance, especially in the outdoor setting. The place kick is a means to score points. Maximizing the distance and accuracy a kicker is able to achieve increases the number of point scoring opportunities available to a team. The hypothesis of this study was that there is a relationship between distance and accuracy and the rotational kinematics of place kicking performance of rugby players in an outdoor setting. Twelve first team university rugby players had full body kinematics measured for five place kicks. Kick distance and accuracy were directly measured. The current study showed a positive correlation between torso (r=0.76) and pelvis (r=0.66) rotation with kick distance. Place kick distance (r=0.24) or accuracy (r=0.54) were not correlated to playing experience. Negative correlations between stance elbow flexion (r=-0.78), torso rotation (r=-0.74) and X-factor (r=-0.79) with kick accuracy were noted. Place kick distance could potentially be maximized by improving torso and pelvic rotations. Place kick accuracy could be improved by full extension of the stance arm. The data suggests that larger torso rotations may promote kicking distance however impede kicking accuracy.

Introduction

The place kick is a means of scoring points either as a penalty kick or converting a try. Quarrie & Hopkins (2015) reported that an average of 45% of the points during a rugby game resulted from successful place kicks. The kicking tee is used to elevate the ball from the ground and encourage the kicker to make a clean strike against the ball. The kicker must have the ability to kick the ball long distances as well as be accurate enough to get the ball through the up-rights, spaced 5.6m apart. Therefore a successful rugby place kick requires accuracy and sufficient velocity to reach the necessary distance. The success of a place kick is currently thought to be reliant on both physiological factors, such as lower body strength (Zhang et al., 2012), and on biomechanical skill, such as the optimization of the kinetic chain (Bezodis et al., 2007; Zhang, et al., 2012).

Physiological improvement to muscular strength following resistance training (Manolopoulos et al., 2013) and a combined strength and kick coordination training intervention (Manolopoulos et al., 2006) have been shown to increase ball speed. Additionally Australian football players that exhibit more accurate place kicks have been shown to have more muscle mass than their inaccurate counterparts (Hart et al., 2013; 2014). While muscular strength and muscle mass are essential to kicking performance, it is likely that kicking requires more than strength alone.

Kicking is a complex biomechanical action that requires the controlled and intricate coordination between the segments of the lower body, both temporally and spatially (Urbin et al., 2011; Bezodis, et al., 2007; Kallis & Katis, 2007; Manolopoulos, et al., 2006; Naito et al., 2010; Shan & Westerhoff, 2005; Urbin, et al., 2011). The kinematics of the kicking action has been studied by many researchers specifically in soccer (reviewed by Lees et al., 2010) and Australian football (Hart, et al., 2014). Previous researchers that have examined the place

kick in rugby have focused on kicking models and kicking performance (Bezodis, et al., 2007, Ball et al., 2013, Sinclair et al., 2014a).

The kick distance is the result of the generation of maximal energy being transferred via the kinetic chain to the ball. To impart maximal velocity to the ball the energy generated should occur in a proximal-distal fashion (Naito, et al., 2010; Shan & Westerhoff, 2005; Sinclair, et al., 2014a; 2014b; Urbin, et al., 2011; Zhang et al., 2012). The initiation of the kicking sequence has been previously suggested to begin with rotation occurring at the pelvis (Kallis & Katis, 2007; Sinclair et al., 2014b; Zhang et al., 2012). Additionally, Lees and colleagues (2010) mentioned the positive relationship between stride length and the resulting kick distance and attributed this relationship to energy generated by the rotation of the pelvis. However more recently Fullenkamp and colleagues (2015) showed the importance of the trunk rotation in attaining ball velocity. Their finding shifts the imitation of the kinetic sequence further up to the level of the torso and needs to be investigated within the rugby context. While these relationships are contributing factors, it is likely that the efficient transfer of energy between segments is more important for achieving distance with the kick (Kellis et al., 2006). Specifically in the rugby place kick, ball velocity has been shown to be related to peak knee extension velocity (Sinclair et al., 2014a), but not as a result of changing the foot plant position (Baktash et al., 2009) likely due to the similar positions of foot placements across the spectrum (Cockcroft & van den Heever, 2015). Within a rugby context longer run ups have shown a trade-off between increased ball velocity and reduced kick accuracy (Padulo et al., 2013).

The trade-off between speed and accuracy has been shown in various sporting disciplines (Sachlikidis & Salter, 2007; García et al., 2013), in the soccer kick (Teixeira, 1999; Asai et al., 2002; Kallis & Katis, 2007) and more specifically in the rugby place kick (Bezodis, et al., 2007; Padulo, et al, 2013).

The study aims to evaluate the kinematic determinants of rugby place kick distance and accuracy on a natural turf outdoor field. It was hypothesized that the rotational kinematics of the shoulder and pelvic girdles, major components in the transfer of energy in the kinetic chain, are related to the achievable distance and accuracy of the place kick. Specifically it was expected that greater shoulder and pelvis rotations would result in further and more accurate place kicks. Following this it was hypothesized that one possible mechanism for achieving maximal distance and accuracy is muscular power. To this end it was expected that lower body power would be related to the place kick distance and accuracy. Collectively the study is expected to give a further biomechanical description of the rugby union place kick recorded in a natural setting.

Methods

Participants

Twelve first team university rugby players (age 22±3 years, mass 89± 2 kg, stature 179±6 cm, playing experience 11±4 years) were recruited to take part in the study. Players were identified as those who would kick for the up-rights during a match and had at least four years experience at the premier league playing level. All participants were all injury free at the time of the study. All tests were conducted in the evening (18:00-21:00) at a similar time to local matches. Written informed consent was received prior to the start of testing and ethical approval was granted by the University Ethics Committee (M131019).

Outcome measures and instrumentation

The place kick outcome measures are divided into two groups: outcomes (distance and accuracy) and inputs (technique and power).

The kick distance was defined as the length from the midpoint on the half way line to the landing position of the ball. Kicking accuracy was measured as follows: a central line was placed along the ground from the midpoint of the halfway line to the middle of the up-rights. The exact landing position of each ball that was kicked, noting whether or not it successfully passed through the up-rights, was measured perpendicularly from the central line to the nearest centimetre, using a tape measure. Accuracy was determined as the angle between the central line and the line from the centre of the field to the position of the ball. The accuracy angle was taken as the absolute angle. An angle of 0° indicates that the ball landed on the central line and achieved 100% accuracy. A larger angle indicates greater deviation from the central target line.

As kicking performance may be dependent on lower body power, an indication of lower body power was determined using a vertical jump. Participants were instructed to crouch down in a squat position and jump as high as possible while keeping their legs fully extended. No arm swinging was permitted, and multiple jump attempts were used during the warm-up routine prior to the test. Participants had three jumping conditions: dominant, non-dominant single leg jumps and a jump using both legs. The jump procedure was repeated twice, with the average jump distance being used for analysis. Pelvic height was tracked kinematically and lower leg power was calculated as the difference in height between the maximal jump height and standing height.

All kinematics (kicking technique) were recorded at 100Hz using an 18 camera system (Optitrack flex:V100r2 (Natural Point Inc., Corvallis, Oregon, USA). A volume of approximately 40 m^3 was calibrated at the halfway line on a rugby field. Calibration and 3D tracking was performed using AMASS (C-Motion Germantown, Maryland, USA). Calibration accuracy was reported to be sub-millimeter. Raw marker trajectories were

imported in to MatLab 7 (Mathworks, Natick, Massachusetts, USA), where biomechanical variables were calculated using custom written algorithms (described later).

Procedure

Prior to testing, participants warmed-up in their own accustomed manner and also practised kicking a ball three times under the experimental conditions. Participants kicked five maximal place kicks from the midpoint on the halfway line. The accuracy constraint was to successfully kick the ball between the up-rights and over the crossbar, and the distance constraint was to achieve maximal forward distance from the halfway line position. Standard training rugby balls (Gilbert XT300 inflated to the regulation pressure of between 65-68kpa) were used and participants used their own accustomed kicking tees, kicking procedure and approach angle.

Each participant performed a vertical jump test either before or after the five place kicks in a randomised manner. The five place kicks and two vertical jumps were tracked kinematically.

Data reduction

The kinematics of each kick was determined using a 42 retroreflective marker set placed on anatomical landmarks which created a 15 segment model. Joint centres were calculated using mathematics similar to the PlugIn Gait (Kadaba et al., 1990 and Gutierrez et al., 2003).

Back flexion was calculated as the angle between the lower back (sacrum to tenth thoracic) vector and upper back (tenth thoracic to seventh cervical) vector. Lateral bend angle was defined as the abduction of the torso plane relative to the pelvic plane. Neutral alignment of the torso sagittal plane relative to the pelvic sagittal plane is indicated by 0°. Arm abduction was calculated as the angle created by the separation between the upper arm vector and the torso. Head, torso and pelvic rotations were calculated as the difference between the global

horizontal vector and the respective body vectors. A positive value for the rotations would indicate an open stance with the support side shoulder directed towards the up-rights. X-factor, a variable widely used in golf research (Chu et al., 2010), was defined as the difference between torso and pelvic rotations. An X-Factor value of 0 indicates that the torso and pelvic girdles are in sequence, a positive value indicates the greater rotation of the torso relative to the pelvic girdle. The elbow flexion was calculated bilaterally, as the angle of flexion between the humerus vector and the vector of the forearm. Similarly the wrist angle was calculated bilaterally, as the angle of flexion between the forearm vector and the vector of the hand. Bilateral knee and ankle flexions were calculated as the angle of flexion between the femur vector and the vector of the shank, and the angle of flexion between the vectors of the shank and the foot, respectively. Flexion value of 0° indicates full extension of the elbows and knees and neutral head and wrist positions. The average for the individual kinematic variables of the five kicks for each of the 12 participants were used for the subsequent analysis.

Statistical analyses

All data variables passed the Shaprio-Wilk normality test and are represented as mean±standard deviation. Pearson's correlations were run between the kicking outcomes and the biomechanical variables and vertical jump parameters in GraphPad Prism 5 (GraphPad, San Diego, California, USA). Qualitative descriptions for the strength of the relationships were defined as: r=0.00-0.25 little or no relationship; r=0.25-0.50 fair relationship; r=0.50-0.75 moderate to good relationship; r>0.75 good to excellent relationship (Portney & Watkins, 2009). Stepwise multiple linear regressions were performed for kick distance and accuracy in MatLab 7. A significance level of $p<0.05$ was applied.

Results

The average kick distance achieved was 45.35±5.27 m, with an average accuracy spread of 6.41±3.57°. There was no significant relationship between kick distance and kick accuracy (r=-0.466; p=0.127). Playing experience was not correlated to the accuracy (r=0.54, p=0.07) or the place kick distance (r=0.24, p=0.44).

The average double leg vertical jump height was 0.52±0.07 m (CV=0.135). The average support leg height was 0.36±0.08 m (CV=0.222), and the average kicking leg height was 0.34±0.07 m (CV= 0.206). No significant relationships were found between the double leg vertical jump power and the distance achieved (r=-0.29; p=0.36) or accuracy (r=0.33, p=0.25) of the kicks. Furthermore no significant relationships were found between the dominant (distance: r=-0.24, p=0.67; accuracy: r=-0.11, p=0.26) and non-dominant (distance: r=-0.18, p=0.76; accuracy: r=-0.13, p=0.21) single leg vertical jump and the outcomes of the kick.

The relationships between distance and accuracy and the kinematic parameters at ball contact are shown in Table 4.1. An excellent relationship was present between the kick distance and the torso rotation (r=0.76) and a moderate to good relationship was found between the kick distance and pelvic rotation (r=0.66). A moderate to good negative relationship was found between the kick accuracy and the torso (r=-0.66), and head (r=0.60) rotations and the stance elbow flexion (r=-0.75). An excellent negative relationship was present between the kick accuracy and X-factor (r=-0.84).

Table 4.1: Kinematic kicking variables at ball contact and the Pearson's correlation coefficients (r) for the distance and accuracy measures.

Kinematic kicking variables	M±SD	Distance (r)	Accuracy (r)
Back flexion (°)	44.6±7.7	0.02	-0.13
Lateral bend (°)	27.6±21.9	-0.12	0.20
Stance arm abduction (°)	131.3±10.2	-0.03	0.22
Kicking arm abduction (°)	52.0±12.7	-0.36	0.21
Head rotation (°)	84.5±9.4	-0.16	**0.60***
Torso rotation (°)	45.4±12.6	**0.76***	**-0.66***
Pelvis rotation (°)	28.2±9.9	**0.66***	-0.08
X-factor (°)	17.1±8.9	0.33	**-0.84***
Head flexion (°)	75.8±12.3	-0.07	-0.27
Stance elbow flexion (°)	22.4±9.6	0.27	**-0.75***
Kicking elbow flexion (°)	24.3±17.3	0.05	0.24
Stance knee flexion (°)	26.1±6.5	-0.04	-0.34
Stance ankle extension (°)	107.3±9.0	0.34	0.28

*Indicates statistical significance ($p<.05$)

The resulting multiple linear regression model for kick distance was able to predict 53% of the kick distance variation (Adjusted R^2=0.53; p=0.005). The only significant contributor was the torso rotation (beta coefficient=0.32). The multiple linear regression model for kick accuracy was able to predict 69% of the kick distance variation (Adjusted R^2=0.69; p=0.002). The significant contributors were the torso rotation (beta coefficient=-0.35) and pelvic rotation (beta coefficient=0.28).

Discussion and conclusions

The primary hypothesis, that the major rotational components of the kinetic chain (the shoulder and pelvic girdles) would be related to the distance of the place kick, was confirmed. Greater shoulder and pelvis rotations were shown to be used when further place kicks were achieved. However more accurate place kicks were shown to have a lower degree of torso rotations, greater head rotations, lower degree of separation between the torso and pelvis and a more flexed stance elbow. While these correlations do not imply causation, they do highlight the importance of the rotational kinematics of the shoulder and pelvic girdles in the generation of kicking distance. One possible mechanism for achieving maximal distance and accuracy was hypothesized to be muscular strength. Contrary to this hypothesis no relationships were found between vertical jump height and place kick distance or place kick accuracy.

Direct measure of kick distance

The mean kicking distance attained in this study of 45.36 m is in agreement with Linthorne and Stokes (2014) whose participants kicked a similar distance. Similarly, this shows that the participants were on the limit of their respective achievable thresholds. Ball and colleagues (2013) reported numerous successful attempts when the place kick was 40m from the goal posts. While the participants range may have been tested past their limits, this study shows the importance of the kick accuracy. The likelihood of achieving a successful attempt at the goals seems to be diminished as the distance from the goals increases (Linthorne & Stokes, 2014). By making the standard position on the halfway line, 50 m from the up-rights, we were able to test the range limits and accuracy of the kicks concurrently.

Kick distance and the kinetic chain

The current study showed a positive, good to excellent correlation between the rotations of the shoulder (torso) and pelvic girdles, and the kick distance. One could assume that the optimal kinetic chain sequence would begin with the rotations of the torso followed by the rotation of the hips to impart optimal velocity to the leg segments. Naito, et al. (2010) showed how trunk rotations could lead to greater knee extension velocities and in effect greater ball velocities. This in the context of the kinetic chain can be misleading as the trunk is not directly related to the legs. The energy generated by the trunk needs to be transferred via the pelvis to the leg. Bezodis, et al. (2007) demonstrated the importance of pelvic rotation in the generation and transfer of energy and Zhang, et al. (2012) showed how pelvis rotation had a small effect on overall foot velocity thus demonstrating the transfer of energy from the trunk to the legs. Recently Fullenkamp, et al. (2015) showed the importance of the trunk rotation in attaining ball velocity. While no relationship was shown in the current study between X-factor and kick distance; a significant relationship between X-factor and kick accuracy was presented. The kinematic variable X-factor, the relative separation of the torso relative to the pelvis, is similar to the trunk axial rotation used in the Fullenkamp, et al. (2015) study. Surprisingly the back flexion and the lateral bend angle at ball contact had no significant relationship with either kick distance or kick accuracy. This lack of relationships may be a result of the experienced nature of the participants within the current study. The regression model for kick distance would tend to agree that torso rotation, being the only significant inclusion, is a larger contributor than pelvic rotations, lateral bend or back flexion.

Upper body contributions

Various biomechanical parameters played a role in kick accuracy in this study. Shan and Westerhoff (2005) showed that skilled soccer players used their upper bodies more effectively when kicking than less skilled players. Additionally skilled kickers were able to find the balance between segment coordination and kinetic chain optimisation (Shan & Westerhoff 2005). The relationships found in the current study suggest that at kick contact, the difference between the torso and pelvic rotations (X-factor) should be minimized in order to achieve a more accurate kick. Furthermore it is possible that simply minimizing the torso rotation could lead to a more accurate kick. The flexion of the stance elbow, while not directly involved with the kick, was shown to have a negative correlation with the kick accuracy. The elbow flexion of the stance arm may indirectly be related to the balance requirements of the kicker (Bezodis, et al., 2007). Less elbow flexion would increase the stance arm moment leading to a greater displacement of the kicker's centre of mass. Interestingly, no relationships were seen between the abduction of the kicking side arm and kick accuracy. Further investigation into the effects of the stance arm, balance and kick accuracy is required.

Degree of kick accuracy

The accuracy in this study was measured as the degree between the landing positions of the balls relative to the midpoint of the halfway line. A lower value indicates a more accurate kick. The margin of error for a successful kick from this distance is 3.21°. The absolute average for the sample of 12 kickers was 6.41±3.57° indicating that the majority of kick attempts, while lacking the distance, were not on target either. While many previous studies have tested accuracy and distance independently indoors, indirectly measuring the performance outcomes (Bezodis, et al., 2007; Zhang, et al., 2012; Sinclair, et al., 2014a), this

is the first study to test both in an outdoor setting. The regression model for kick accuracy indicated that contributions from the torso and pelvic girdle are essential in the attainment of an accurate kick.

Distance accuracy trade off

The positive correlations for distance and the negative correlations for the accuracy would suggest that the kinematic contributors, specifically the torso rotation, would impede one another. Similar relationships have been shown by previous studies focusing specifically on the instep kick in soccer (Asai, et al., 2002; Kallis & Katis, 2007; Teixeira, 1999) and in rugby place kicking studies (Bezodis, et al., 2007; Padulo, et al., 2013). The change in ball velocity must stem from the development of the power through the kinetic chain and therefore the kinematic parameters should be different. The results in the current study would suggest that some of the relationships between the kinematics and distance and accuracy are antagonistic. Although it would seem that the contributions from the upper body, specifically the torso rotations, is the underlying determinant when distinguishing between place kick distance and accuracy. The torso rotations, which were positively correlated to the distance and negatively correlated to the accuracy spread, could be a minor contributor to the overall kick distance with the pelvis rotation the main contributor. However the shoulder contribution to the accuracy might be a more important relationship. The additional relationship shown between the accuracy and the X-Factor may in part confirm the importance of the torso rotation in accuracy. The lack of a significant relationship between X-Factor and distance may be a result of the timing of the rotations between the shoulder and pelvic girdles. The peak velocities of these girdles and their effect on kick distance and accuracy need to be investigated further.

Lower body power

Hart and colleagues (2014) suggested that muscle alone doesn't make an accurate or powerful kicker, but increased muscle mass could contribute and should be a major component of the optimal kicking system. Supporting this concept is research showing lower leg strength in soccer instep kicks to be a performance predictor for kick distance (Manolopoulos et al., 2006; Fousekis et al., 2010; Manolopoulos, et al., 2013). The lack of a significant relationship between lower body power and kick distance suggests that place kicking requires more than pure leg strength or may be an effect of the intrinsic power capacity exhibited by all rugby players or the simplified nature of the vertical jump test. Other components that could predict kick performance may include balance, flexibility, proprioception and coordination. These parameters require further investigation. Furthermore the timing of the limb segments (Urbin, et al., 2011) and the coordination of the muscle fiber contractions (Hart, et al., 2014; Scurr et al., 2011) may prove to be contributing determinants of distance kicking ability. While no relationship between playing experience and kick accuracy ($r=0.54$; $p=0.07$) was found in the current study, it is likely that skilled players have a better physiological capacity of the requirements for an accurate kick, and that this capacity develops with experience.

Limitations

A limitation of the current study was the speed of the kinematic system, which was not effective in reliably capturing the kicking leg. The use of a small sample amateur group of players is another limitation of the study as the results may not be generalizable to higher skilled players who may be using other strategies to generate distance and accuracy. Additionally amateur player may not have the ability to consistently have accurate kicks on the limit of their range. The outdoor setting, whilst providing representative data, had

constraints regarding mobility of equipment and required the use of simple field tests. Further studies could utilize more robust strength and flexibility tests. Finally, more robust statistical analysis is warranted for future studies as the current study makes use of correlations, which cannot imply causation.

In conclusion, the current study showed how distance could be maximized by improving the rotations of the torso and pelvis segments and accuracy of the kick could be improved by full extension of the stance arm. Biomechanical parameters that promote the kick distance, specifically torso rotation, may impede the kick accuracy.

Possible applications for practitioners

Our data suggests that larger torso rotations may promote place kick distance but may impede place kick accuracy.

To achieve further place kick distances a larger rotation of the shoulder and the pelvic girdles prior to ball contact should be encouraged.

Place kick accuracy could be improved by fully extending the stance arm and by maximizing the separation between the shoulder and pelvic girdles prior to ball contact.

References

Asai, T., Carré, M. J., Akatsuka, T. & Haake, S.J. (2002). The curve kick in football I: impact with the foot. *Sports Engineering*, 5: 183-192.

Baktash, S., Hy, A., Muir, S., Walton, T. & Zhang, Y. (2009). The effects of different instep foot positions on ball velocity in place kicking. *International Journal of Sports Science and Engineering*, 3(2): 85-92.

Ball, K., Talbert, D. & Taylor, S. (2013). Biomechanics of goal-kicking in rugby league. In Nunome, H., Drust, B. & Dawson, B., (Eds). Science and Football VII 47-52. New York: Routledge.

Bezodis, N., Trewartha, G., Wilson, C. & Irwin, G. (2007). Contributions of the non-kicking-side arm to rugby place-kicking technique. *Sports Biomechanics*, 6(2): 171-186.

Chu, Y., Sell, T.C. & Lephart, S.M. (2010). The relationship between biomechanical variables and driving performance during the golf swing. *Journal of Sports Sciences*, 28: 1251-1259.

Cockcroft, J. & van den Heever, D. (2016). A descriptive study of step alignment and foot positioning relative to the tee by professional rugby union goal-kickers. *Journal of Sports Sciences*, 34(4):321-329.

Fousekis, K., Tsepis, E. & Vagenas, G. (2010). Lower limb strength in professional soccer players: profile, asymmetry, and training age, *Journal of Sports Science and Medicine*, 9: 364-373.

Fullenkamp, A.M., Campbell, B.M., Laurent, C.M. & Lane, A.P. (2015). The contribution of trunk axial kinematics to poststrike ball velocity during maximal instep soccer kicking. *Journal of Applied Biomechanics*, 31: 370-376.

García, J.A., Sabido, R., Barbado, D. & Moreno, F.J. (2013). Analysis of the relation between throwing speed and throwing accuracy in team-handball according to instruction. *European Journal of Sport Science,* 13: 149-154.

Gutierrez, E.M., Bartonek, A., Haglund-Akerlind, Y. & Saraste, H. (2003). Centre of mass motion during gait in persons with myelomeningocele. *Gait and Posture,* 18: 37-46.

Hart, N.H., Nimphius, S., Cochrane, J.L. & Newton, R.U. (2013). Leg mass characteristics of accurate and inaccurate kickers-an Australian football perspective. *Journal of Sports Sciences*, 31: 1647-1655.

Hart, N.H., Nimphius, S., Spiteri, T. & Newton, R.U. (2014). Leg strength and lean mass symmetry influences kicking performance in Australian football. *Journal of Sports Science and Medicine*, 13: 157-165.

Kadaba, M.P., Ramakrishnan, H.K. & Wooten, M.E. (1990). Lower extremity kinematics during level walking. *Journal of Orthopaedic Research,* 8: 849-860.

Kallis, E. & Katis, A. (2007). Biomechanical characteristics and determinants of instep soccer kick. *Journal of Sports Science and Medicine*, 6: 154-165.

Kellis, E., Katis, A. & Vrabas, I.S. (2006). Effects of an intermittent exercise fatigue protocol on biomechanics of soccer kick performance. *Scandinavian Journal of Medicine and Science in Sports*, 16: 334-344.

Lees, A., Asai, T., Andersen, T. B., Nunome, H. & Sterzing, T. (2010). The biomechanics of kicking in soccer: A review. *Journal of Sports Sciences*, 28: 805-817.

Linthorne, N.P. & Stokes, T.G. (2014). Optimum projection angle for attaining maximum distance in a rugby place kick. *Journal of Sports Science and Medicine*, 13: 211-216.

Manolopoulos, E., Katis, A., Manolopoulos, K., Kalapotharakos, V. & Kellis, E. (2013). Effects of a 10-week resistance exercise program on soccer kick biomechanics and muscle strength. *Journal of Strength and Conditioning Research*, 27(12): 3391-3401.

Manolopoulos, E., Papadopoulos, C. & Kellis, E. (2006). Effects of combined strength and coordination training on soccer kick biomechanics in amateur players. *Scandinavian Journal of Medicine and Science in Sports*, 16: 102-110.

Naito, K., Fukui, Y. & Maruyama, T. (2010). Multipoint kinetic chain analysis of knee extension during the soccer instep, *Human Movement Science*, 29: 259-276.

Padulo, J., Granatelli, G., Ruscello, B. & D'ottavio, S. (2013). The place kick in rugby. *Journal of Sports Medicine and Physical Fitness*, 53(3): 224-231.

Portney, L.G., & Watkins, M.P. (2009). *Foundations of Clinical Research: Applications to Practice*, 3rd edn., Pearson Prentice Hall: London.

Quarrie, K.L. & Hopkins, W.G. (2015). Evaluation of goal kicking performance in international rugby union matches. *Journal of Science and Medicine in Sport*, 18: 195–198.

Sachlikidis, A. & Salter, C. (2007). A biomechanical comparison of dominant and non-dominant arm throws for speed and accuracy. *Sports Biomechanics*, 6: 334-344.

Scurr, J.C., Abbott, V. & Ball, N. (2011). Quadriceps EMG muscle activation during accurate soccer instep kicking. *Journal of Sports Sciences*, 29: 247-251.

Shan, G. & Westerhoff, P. (2005). Full body kinematics characteristics of the maximal instep soccer kick by male soccer players and parameters related to kick quality. *Sports Biomechanics*, 4(1): 59-72.

Sinclair, J., Taylor, P. J., Atkins, S., Bullen, J., Smith, A. & Hobbs, S. J. (2014a). The influence of lower extremity kinematics on ball release velocity during instep place kicking in rugby union. *International Journal of Performance Analysis in Sport*, 14: 64-72.

Sinclair, J., Fewtrell, D., Taylor, P.J., Bottoms, L., Atkins, S. & Hobbs, S.J. (2014b). Three-dimensional kinematic correlates of ball velocity during maximal instep soccer kicking in males. *European Journal of Sport Science*, 14: 799-805.

Teixeira, L.A. (1999). Kinematics of kicking as a function of different sources of constraint on accuracy. *Perceptual and Motor Skills*, 88: 785-789.

Urbin, M.A., Stodden, D.F., Fischman, M.G., & Weimar, W.H. (2011). Impulse-Variability Theory: Implications for ballistics multijoint motor skill performance. *Journal of Motor Behavior*, 43: 275-283.

Zhang, Y., Liu, G. & Xie, S. (2012). Movement sequences during instep rugby kick: a 3D biomechanical analysis. *International Journal of Sports Science and Engineering*, 6(2), 89-95.

Chapter 5:

A kinematic comparison between the rugby union place kick and drop kick. Andrew Green, Samantha Kerr, Benita Olivier, Chloe Dafkin and Warrick McKinon.

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Abstract

In the game of rugby union, two kicking methods are used to score points: the place and the drop kicks. With nearly half of the points in a rugby match scored through kicking, the place kick is a more structured manoeuvre and provides a greater chance of scoring success. The aim of this study was to compare the kinematics of these two kicking techniques. Nine university level rugby players (age: 23±3years; mass: 87.2±9.4kg) kicked five maximal place/drop kicks from the halfway line on a rugby field. Kicking kinematics were obtained using a high speed camera system and kick distances were directly measured. Place kicks were significantly further ($p=0.02$) and as accurate as drop kicks ($p=0.493$). Torso rotation angle was significantly smaller in the drop kick and the rotational velocity of the torso was significantly higher in the drop kick midway through the kicking cycle. No observable differences were detected in the stance arm abduction angle. Kicking knee flexion was significantly different early in the kicking sequence. The results indicated that apart from a few differences in the early stages the kicking sequences were very similar, suggesting that the body kinematics used during the place and drop kicks are not dissimilar.

Introduction

In rugby, kicking can be used to gain territorial advantage over the opposition and is also a key strategy available to a team to score points. In particular, the place kick is a set phase to the game and is used primarily as an attempt at goals either from a penalty or attempted conversion of a try. Quarrie & Hopkins (2015) have shown the importance of successful kicks with an average of 45% of points during the game coming from the place kick. While the drop kick can be used to score points it is primarily used to gain a territorial and tactical advantage over the opposition either from the kick-off or restarting from within the 22 metre area.

The success of a kick has been kinematically related to the rotation of the shoulder girdle (Naito et al., 2010; Sinclair et al., 2013; Fullenkamp et al., 2015) the degree of the stance side arm abduction; Bezodis et al. (2007), stance leg balance (Chew-Bullock et al., 2012) and the extension of the kicking knee (Zhang et al., 2012; Sinclair et al., 2014a; Sinclair et al., 2014b).

Distinct differences between the place kick and the drop kick exist. Firstly, the place kick is a closed skill and makes use of a kicking tee, to elevate the ball from the turf to ensure a cleaner contact between ball and foot. The drop kick can be considered as an open skill and is one of the most unique aspects of rugby kicking, where the ball is dropped onto the turf and kicked upon rebound. The shape of the ball requires the kicker to drop the ball as close to the apex as possible to ensure a good (predictable) rebound. The drop kick therefore has more dynamic elements, in the sense that it requires the kicker to drop the ball onto the turf and make contact between the foot and ball once the ball has rebounded upwards.

Guidelines established by the World Rugby online coaching manuals (World Rugby Coaching Website) suggest a few similarities between the two kick types. Firstly the part of

foot used to make contact with the ball is the same, dorsal part of the foot, corresponds to the position of the laces on the boot. Secondly kickers are encouraged to align their shoulder girdle so that the non-kicking side is directed towards the target. The final similarity as suggested by the World Rugby online coaching manuals is for kickers to use their non-kicking side arm for balance during the kicking sequence.

The main mechanistic difference between the drop kick and place kick is the need to drop the ball onto the turf. This intrinsic requirement would therefore likely lead to differences in arm (and shoulder) kinematics between kicking types. Two additional mechanistic differences are however also evident and could potentially differentiate the kinematics of the drop- and place-kick: stance leg flexions and kicking leg segment velocities, as describe hereafter.

The stance leg during the place kick might experience more flexion than the drop kick. The drop kick being more dynamic may require the kicker to adjust their body height relative to the ball. One mechanism that might be used is by changing the flexions at the knee joints.

Based on the rationale above and prior to the current study, four determinants of kicking performance in rugby were identified: the rotation of the shoulder girdle; the degree of stance side arm abduction; stance leg and kicking leg and knee flexions. The study aimed to investigate the similarities or differences in these four specific parameters in the place and drop kick. It was hypothesised that the degree of shoulder rotations would be similar between the two kicking types. Secondly arm kinematics will be different with smaller stance side arm abductions present in the drop kick. Thirdly the degree of knee flexion in the stance leg was expected to be greater in the place kick than the drop kick. Finally no differences in the degree of angular velocity of the kicking knee were expected between the two kicking types.

Methods

Participants

Nine First team university level rugby players (age: 23±3years; body mass: 87.2±9.4kg; height: 177±6cm) were recruited to take part in the study. All participants were injury free at the time of the study and were identified as those who would kick for points during a match. Only players that would normally kick for goals during a game were invited to take part in the study. Ethical approval was granted by the University Ethics Committee (M131019) and written informed consent was received prior to the start of testing.

Procedure

Participants underwent a self-guided warm-up prior to testing. All participants were allowed no more than three practise kicks under the experimental conditions. Following this, participants were instructed to kick five maximal place kicks and five maximal drop kicks from the midpoint on the halfway line, with the aim in each case to achieve a successful kick (over the crossbar, between the uprights). The kicking order was randomised between participants. A set of standardised training rugby balls were used and participants were allowed to use their own accustomed kicking tees for place kicks. No restrictions regarding the kicking procedures (approach angles or approach speed) for place kicks and drop kicks were enforced.

Instrumentation and outcome measures

All kicking kinematics were recorded using an 18 camera system at 100Hz (Optitrack flex:V100r2 (Natural Point Inc., Corvallis, Oregon, USA)). A volume large enough to capture the kicking sequence was calibrated at the halfway line on a rugby field. Calibration and 3D tracking was performed using AMASS (C-Motion Germantown, Maryland, USA).

Calibration accuracy was reported to be sub-millimetre. All biomechanical variables were calculated in MatLab 7 (Mathworks, Natick, Massachusetts, USA) using custom written algorithms (described below). Outcome measures included kick distance, body kinematics (described below) and the linear velocities of the kicking thigh and shank segments. The landing position of each ball that was kicked was marked and directly measured. The kick distance was defined as the length from the midpoint on the half way line to the landing position of the ball.

Kinematic Data reduction

A 42 retroreflective marker set placed on specific anatomical landmarks was used to create a 15 segment model. Mathematics similar to The Plug-In Gait model was used to calculate the joint centres (Kadaba et al., 1990; Gutierrez et al., 2003). One retroreflective marker was placed on the dorsal apex of the ball to determine the point of contact between the ball and foot.

Torso rotations were calculated as the difference between the global horizontal vector and the vector between the shoulder joints. A positive value for the rotations would indicate an open stance with the support side shoulder directed towards the up-rights. Arm adductions were calculated as the difference in angle between the humerus vector and the sagittal plane of the torso. Knee flexions were calculated as the angle of flexion between femur vector and the vector of the shank.

The mean values for the five place kicks and five drop kicks for the kinematics of all nine participants were used in subsequent analysis. The kinematics were analysed from the frame of toe-off of the kicking foot (0%) to the frame at which the foot made contact with the ball (100%).

Statistical analysis

All data were tested for normality using a Shapiro Wilk normality test. Compliant data were compared using a paired Student's t-test. Qualitative descriptions for the differences between the place kicks and drop kicks are reported as effect size using Cohen's d (d=0.2 small effect; d=0.5 moderate effect; large effect d=0.8) calculated using the Hopkins (2007) statistical approach. All remaining statistical procedures were performed in GraphPad Prism 5 (GraphPad, San Diego, California, USA) with a significance level of $p<0.05$.

Results

Participants' data

The average place kick distance was 46.1±4.7m and an average drop kick distance was 42.4±5.0m. The distance of the drop kick was significantly shorter than the place kick (p=0.02). All kickers, apart from two, had further place kicks than drop kicks (Figure 1). The effect is considered to be moderate to large (*d*= 0.76). The absolute kicking error for the place kick was 4.81±3.30m and 5.71±2.37m for the drop kick. No significant difference was observed between the kicking accuracies (p=0.493; d=-0.313).

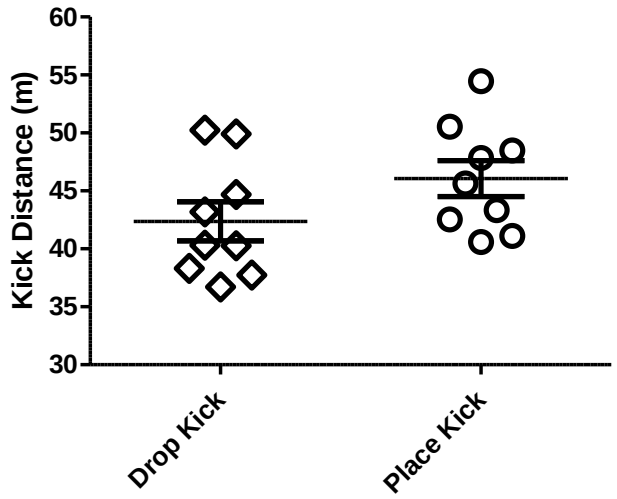


Figure 5.1: The average individual kick distances for the place kicks and drop kicks. Place kicks were significantly further than drop kicks (p=0.02).

Torso rotations

The torso rotation shows differences at 10% (p=0.02) and 20% (p=0.03) of the kicking cycles between the two kicking types (Figure 2 A). The place kick exhibited more rapid torso rotation velocities at 30% (p=0.03), 40% (p=0.04) and 60% (p=0.03) of the kicking cycle (Figure 2 B).

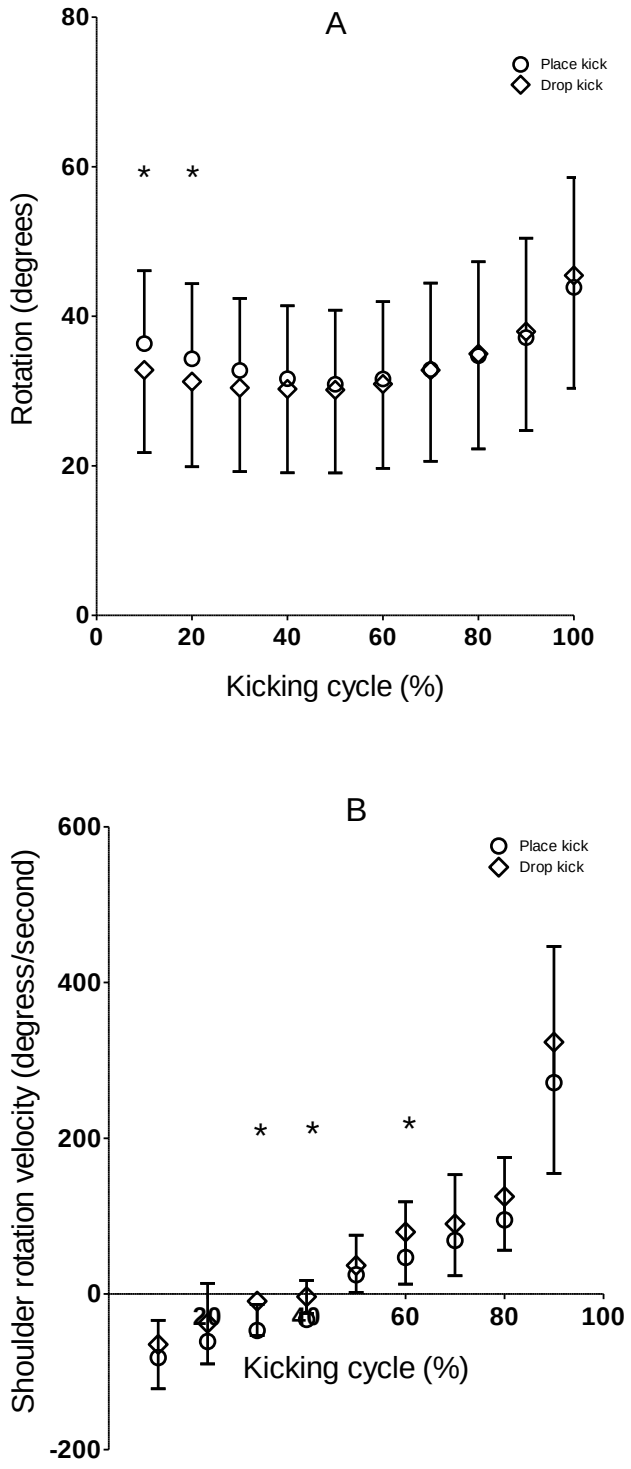
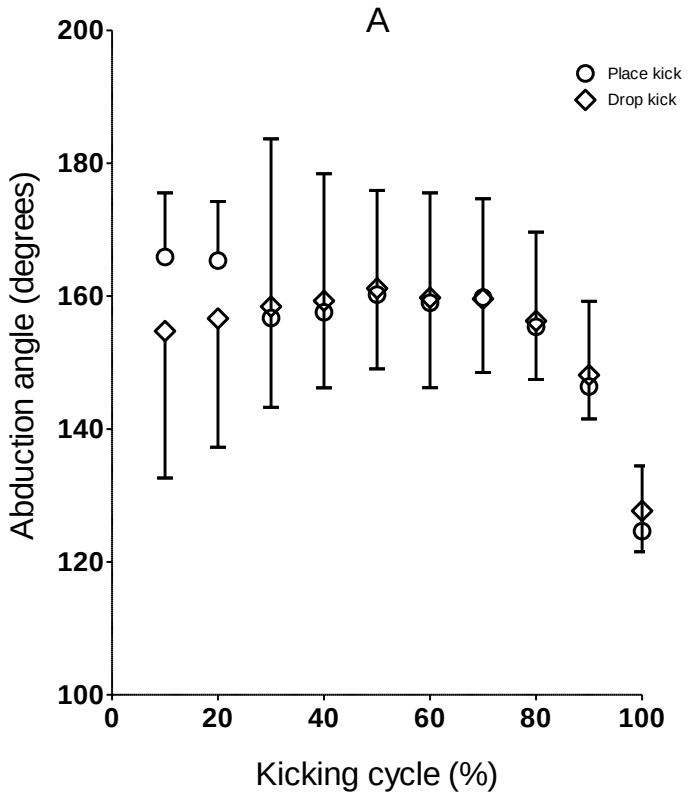


Figure 5.2: Torso rotation angles (A), and shoulder rotational velocities (B) of the subject group when performing place kicks (open circles) or drop kicks (open diamonds) over the kicking cycle (0% indicates kicking foot 'toe off'; 100% indicates kicking football contact). * indicates significant difference between drop kicks and place kicks ($p<0.05$).

Arm kinematics

The adduction angle of the stance-side arm tended towards increasing in the drop kick, while the difference was not significant the effect size is classified as moderate. No differences in the absolute angle or velocities were identified for the stance-side arm adduction. Figure 3A indicates a non-significant but visible difference in the stance-side arm adduction between the two kicking types in the early (10-20%) of the kicking cycles. No observable or statistical difference was reported for the abduction velocity (Figure 3B).



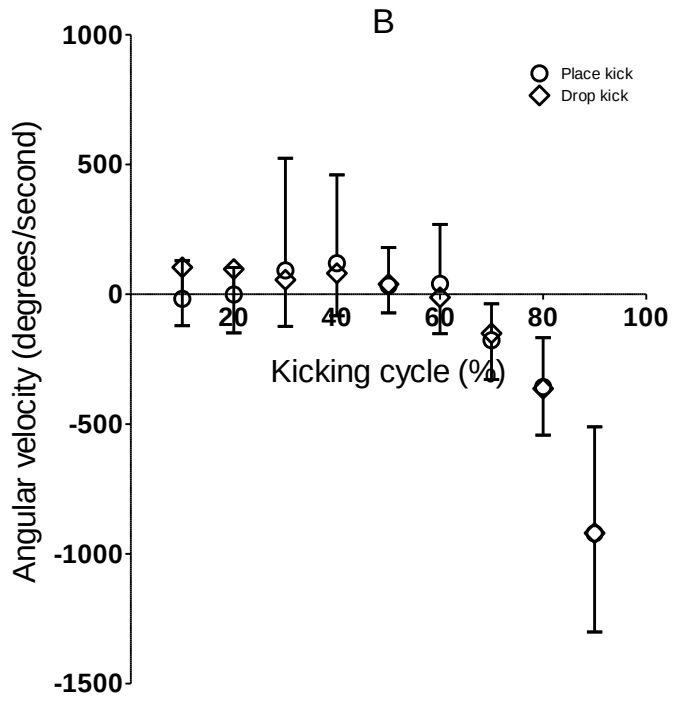


Figure 5.3: Arm abduction angle (A) and velocity (B) of the subject group when performing place kicks (open circles) or drop kicks (open diamonds) over the kicking cycle (0% indicates kicking foot 'toe off'; 100% indicates kicking football contact). * indicates significant difference between drop kicks and place kicks ($p<0.05$).

Knee flexions

The place kick exhibited larger kicking knee flexions at 10% ($p= 0.008$) and 20% ($p= 0.04$) (Figure 4 A) and larger stance knee flexions at 10% ($p= 0.02$) (Figure 5 A) of the kicking cycle. No differences were exhibited for the angular velocities for the kicking or stance knees (Figures 4 B and 5 B).

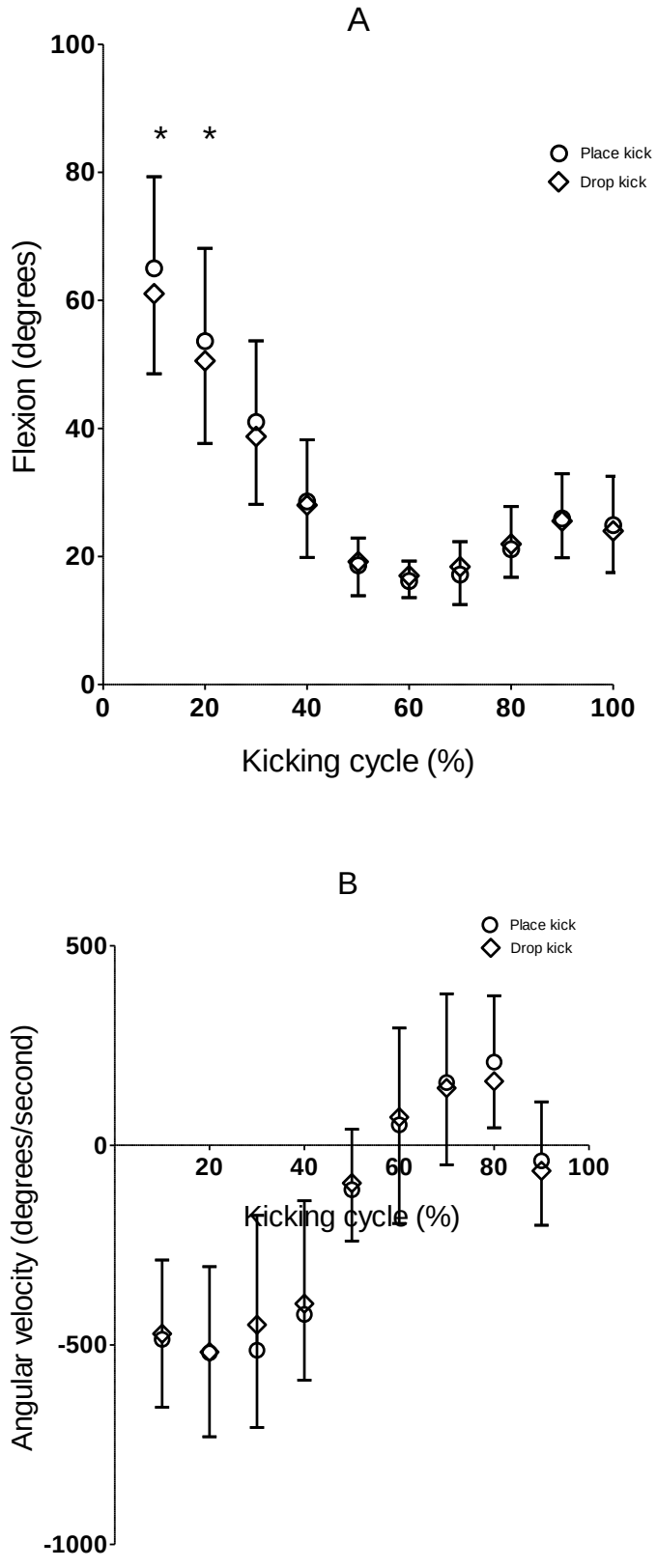
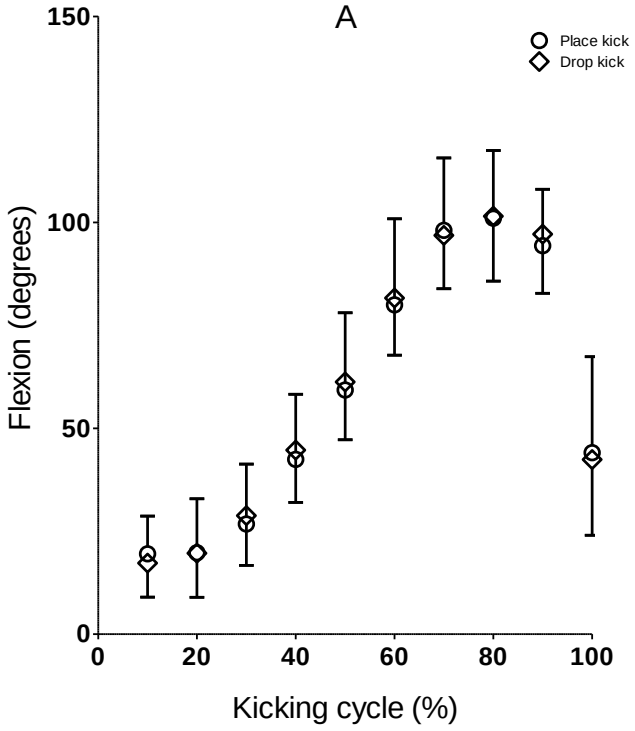


Figure 5.4: Kicking Knee flexion angle (A) and velocity (B) of the subject group when performing place kicks (open circles) or drop kicks (open diamonds) over the kicking cycle

(0% indicates kicking foot ‘toe off’; 100% indicates kicking football contact). * indicates significant difference between drop kicks and place kicks ($p<0.05$).



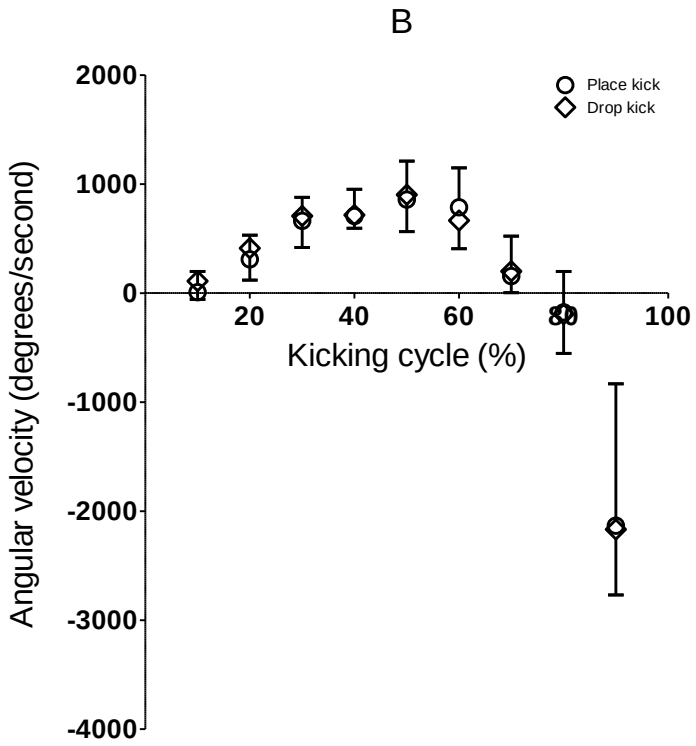


Figure 5.5 Stance knee flexion angle (A) and velocity (B) of the subject group when performing place kicks (open circles) or drop kicks (open diamonds) over the kicking cycle (0% indicates kicking foot 'toe off'; 100% indicates kicking football contact). * indicates significant difference between drop kicks and place kicks ($p<0.05$).

Discussion

The study aimed to investigate for the first time, the similarities and/or differences in the movement patterns used by rugby union kickers to perform place and drop kicks. To do this, the rotation of the shoulder girdle; the degree of the stance side arm abduction; stance and knee flexions in the place and drop kick were assessed. Under no standardised influence, it was found that place kicks were significantly further but no more accurate than drop kicks. It was hypothesised that a similar degree of shoulder rotations would be present between the two kicking type. However the drop kick showed reduced rotations early in the kicking

sequences with increased angular velocities between 40-60% of the sequence. Secondly stance side arm abductions were expected to be smaller in the drop kick. No significant differences were observed throughout the kicking sequence, although a moderate effect size was reported at ball contact. Thirdly the degree of knee flexion in the stance leg was expected to be greater in the place kick than the drop kick. No significant differences were observed for the duration of the kicking sequence. Finally no differences in the degree of angular velocity were expected between the two kicking types. Indeed no differences were exhibited in the angular velocity of the kicking knee.

Differences in the kick outcomes

The outcome of a rugby game may rely on the kicking performance of the team (Quarrie and Hopkins, 2015). One contributor to kick success is the distance of the kick (Nel, 2013; Quarrie and Hopkins, 2015) with kick success decreasing with increasing distance. A significant moderate to large difference was present between the place- and drop-kick. The difference may be attributed to the interaction between foot and ball (Asai et al., 2002) and; the trajectory of the resulting kick (Holmes et al., 2006; Linthorne & Stokes, 2014). Holmes et al. (2006) showed no major difference in the kick distances achieved between the place kick and the drop kick in elite club ruby players however there was a difference in the launch angles between the two types of kicks. Additionally, Linthorne and Stokes (2014) showed an inverse relationship between the projectile velocity of the rugby ball and the projection angle of the kick. The changes between the projectile velocity of the rugby ball and the projection angle of the kick might be a result of different body strategies or simply a change in body mechanics. Although the kick projection angle was not measured in the current study the difference in kick distances could be due to a change in kick projection angle rather than the kick kinematics.

Differences in upper-body kinematics

The World Rugby coaching manual emphasizes the importance of orientation the shoulder girdle (torso) toward the intended target. Additionally Fullenkamp and colleagues (2015) reported a moderate relationship between the velocities of the trunk rotation and the resulting ball velocity. These two findings identify the importance of upper body rotations in both performance aspects of the kick, namely ball velocity and accuracy. The data within the current study has identified differences in the shoulder girdle in the early stage of the sequence. It would seem that the velocity of the rotations is higher during the middle portion of the sequence in the drop kick. This increased velocity may allow the torso rotation to 'catch-up' to a similar value by the time ball contact is made.

The hand used to deliver the ball during a drop punt on the kick distance in rugby players is important (Pavely et al., 2010). The kicking-side hand is normally used to guide the ball down for the attempted kick, either a punt or a drop kick. Pavely and colleagues (2010) showed that using the stance-side hand or both hands reduced the kick distance of the punt. This kicking action may impede the balance of the kicker, thereby reducing their ability to achieve optimal balance while performing a dynamic task suck as kicking (Hrysomallis, 2011; Shan & Westerhoff, 2005). Bezodis and colleagues (2007) demonstrated the importance of the non-kicking side arm (stance-side in this case) in attaining maximal kick distance and accuracy. The contribution of the non-kicking side arm was shown to increase the rotational velocity of the kicking leg. The lack of kicking-side arm abduction differences was unexpected as it was anticipated that the drop kick would exhibit a lower degree of arm abduction. This notion was devised from the technical aspects of the drop kick, in which the kicker would use their kicking-side arm to drop the ball onto the turf. The stance side kicking arm exhibited a lower, but not significant degree of abduction in the early phases of the kicking cycle. Similarly there was no difference in the velocities of the stance side arm

abduction. It was expected that the velocity of the stance side arm would have been greater in the drop kick as the arms are used to guide the ball towards the ground.

Similarities in lower-body kick kinematics

The stance knee flexions showed no significant difference and a small effect. Comparisons during the kicking cycle displayed differences in the early stages of the kicking cycle. These differences could be attributed to the dynamic nature of the drop kick, during which minor adjustments in the step sequence are made. Barbieri and colleagues (2010) showed how body adjustments were made depending on the dynamic nature of the kick. While no differences were reported in the foot velocities there were adjustments in the hips and ankles of the participants when kicking a rolling ball compared to a static ball. It is difficult to make this type of comparison in the current study. Markovic and colleagues (2006) showed no difference in ball velocities between an in-step kick and drop punt kick using a soccer ball in a group of untrained students. However it must be noted that the shape of the ball and the type of kick in respect to the position of ball striking on the foot are different to rugby. Regardless of the different ball shapes it would be expected that a change in kicking type would alter the kinematics and therefore the resulting performance of the kick.

Limitations

The current study is limited by the lack of ball related outcomes such as: ball velocity; launch angle; and spin rate. Additionally the outdoor setting, while providing a better representation of conditions, is limited by the use of permanently set laboratory equipment. A higher capturing frame rate and a larger sample size would have allowed for a more detailed analysis of the two kicking types.

Practical applications

The similarities between the kinematics of the place kick and the drop kick may allow for coaching techniques currently used in the place kick to be applied to the drop kick.

Conclusion

This paper aimed to serve as a biomechanical descriptor of the place kicks and drop kicks in university level rugby players. The results of the current study showed a moderate to large effect in the kick distances of the place kick and drop kick. The kinematics used to achieve the distances do not significantly differ between kicking types. Further research should investigate the differences in kicking foot kinematics and muscular coordination patterns between the place kick and drop kick.

References

Asai, T., Carré, M. J., Akatsuka, T. & Haake, S.J. (2002). The curve kick in football I: impact with the foot. *Sports Engineering*, 5: 183-192.

Barbieri, F.A., Gobbi, L.T.B., Santiago, P.R.P. & Cunha, S.A. (2010). Performance comparisons of the kicking of stationary and rolling balls in a futsal context. *Sports Biomechanics*, 9(1): 1-15.

Bezodis, N., Trewartha, G., Wilson, C. & Irwin, G. (2007). Contributions of the non-kicking-side arm to rugby place-kicking technique. *Sports Biomechanics*, 6(2): 171-186.

Chew-Bullock, T.S.Y., Anderson, D.I., Hamel, K.A., Gorelick, M.L., Wallace, S.A. & Sidaway, B. (2012). Kicking performance in relation to balance ability over the support leg. *Human Movement Science,* 31(6): 1615-1623.

Fullenkamp, A.M., Campbell, B.M., Laurent, C.M. & Lane, A.P. (2015). The contribution of trunk axial kinematics to poststrike ball velocity during maximal instep soccer kicking. *Journal of Applied Biomechanics*, 31(5): 370-376.

Gutierrez, E.M., Bartonek, A., Haglund-Akerlind, Y. & Saraste, H. (2003). Centre of mass motion during gait in persons with myelomeningocele. *Gait and Posture,* 18(2): 37-46.

Holmes, C., Jones, R., Harland, A. & Petzing, J. (2006). Ball Launch Characteristics for Elite Rugby Union Players. In: E.F. Moritz & S. Haake (Eds), *The engineering of sport 6* (pp. 211-216). New York: Springer.

Hopkins, W.G. (2007). A spreadsheet for deriving a confidence interval, mechanistic inference and clinical inference from a p value. Sportscience 11: 16-20 (sportsci.org/2007/wghinf.htm).

Hrysomallis, C. (2011). Balance ability and athletic performance. *Sports Medicine,* 41(3): 221-232.

Kadaba, M.P., Ramakrishnan, H.K. & Wooten, M.E. (1990). Lower extremity kinematics during level walking. *Journal of Orthopaedic Research*, 8(3): 849-860.

Linthorne, N.P. & Stokes, T.G. (2014). Optimum projection angle for attaining maximum distance in a rugby place kick. *Journal of Sports Science and Medicine,* 13(1): 211-216.

Markovic, G., Dizdar, D. & Jaric, S. (2006). Evaluation of tests of maximum kicking performance. *Journal of Sports Medicine and Physical Fitness*; 46(2): 215-220.

Naito, K., Fukui, Y. & Maruyama, T. (2010). Multipoint kinetic chain analysis of knee extension during the soccer instep, *Human Movement Science*, 29(2): 259-276.

Nel, J. (2013). Estimating success probability of a rugby goal kick and developing a measure for ranking rugby union goal kickers. *South African Journal for Research in Sport, Physical Education and Recreation*, 35(1): 133-142.

Pavely, S., Adams, R.D., Di Francesco, T., Larkham, S. & Maher, C.G. (2010). Bilateral clearance punt kicking in rugby union: effects of hand used for ball delivery. *International Journal of Performance Analysis of Sport,* 10(1): 187-196.

Quarrie, K.L. & Hopkins, W.G. (2015). Evaluation of goal kicking performance in international rugby union matches. *Journal of Science and Medicine in Sport*, 18(2): 195–198.

Shan, G. & Westerhoff, P. (2005). Full body kinematics characteristics of the maximal instep soccer kick by male soccer players and parameters related to kick quality. *Sports Biomechanics*, 4(1): 59-72.

Sinclair, J., Taylor, J.P., Atkins, S. & Hobbs, S.J. (2013). Upper body kinematic predictors of ball velocity during out of hand kicking in international level rugby league kickers. *International Journal of Sports Science and Engineering*, 7(2):101-110.

Sinclair, J., Fewtrell, D., Taylor, P.J., Bottoms, L., Atkins, S. & Hobbs, S.J. (2014a). Three-dimensional kinematic correlates of ball velocity during maximal instep soccer kicking in males. *European Journal of Sport Science*, 14(8): 799-805.

Sinclair, J., Taylor, P. J., Atkins, S., Bullen, J., Smith, A. & Hobbs, S. J. (2014b). The influence of lower extremity kinematics on ball release velocity during instep place kicking in rugby union. *International Journal of Performance Analysis in Sport*, 14(1): 64-72.

World Rugby Coaching Website. http://coaching.worldrugby.org/?module=1&section=3&subsection=16. Accessed 01/10/2015

Zhang, Y., Liu, G. & Xie, S. (2012). Movement sequences during instep rugby kick: a 3D biomechanical analysis. *International Journal of Sports Science and Engineering*, 6(2): 89-95.

Chapter 6:

The calibration and application of an individual scrummaging ergometer. Andrew Green, Samantha Kerr, Chloe Dafkin and Warrick McKinon. This manuscript is published in the journal *Sports Engineering* 19(1): 59-69. DOI 10.1007/s12283-015-0188-0.

Abstract

Although the characteristic morphology of rugby forwards playing different positions in the rugby scrum have been well documented, a complete picture of the force characteristics that different players produce has not been evaluated. This is especially true for the movement of the centre of pressure (CoP) elicited during scrummaging in a forward direction. An individual scrummaging ergometer was therefore developed to measure the CoP of an individual scrum action using conventional torque calculations. Calibration of the measurement system revealed measured force errors within 16.6N of the actual force and errors of less than 3.96mm for CoP location determination. Thirty-nine club level rugby union players (22 front rows, 11 locks and six back rows) scrummed against the ergometer on an outdoor rugby field. Differences between the three groups were tested using one-way ANOVAs. The maximum force for different players was 2253.6 ± 649.0N over the entire subject group. There were no differences in the individual compressive force between the groups (front rows: 2404.0 ± 650.3N; locks: 2185.6 ± 568.9N; back rows: 1826.9 ± 670.2N ($p=0.143$)). Individually, front rows started at a higher position than back rows ($p=0.009$) and were at a higher vertical position than locks when producing maximum force ($p=0.028$). Front rows had lower variation in the CoP ($p=0.044$) and less movement to achieve their maximum force ($p=0.020$) than locks. Front rows moved less overall than back rows ($p=0.028$) during the scrum trial. The design and application of the individual scrum ergometer showed with good limits of agreement that differences in force magnitude and CoP exist within scrummaging players. Practically, the application of this ergometer may assist in the individual optimisation of scrummaging performance.

Introduction

The scrum is an entirely unique aspect to rugby, and is designed as a contestable means to restarting the game after a minor transgression has occurred (World Rugby Rule 20.1a). The scrum is composed of eight individual players, packed together, with the intention of generating greater linear momentum than the opposing scrum in an attempt to keep/regain control of the ball. An effective scrum requires the coordinative power of the team (Quarrie & Wilson, 2000; du Toit et al., 2005). To this end researchers have shown that scrummaging power is not only determined by the combined mass of the scrum but is also determined by the technique and timing of the force contributions of scrummaging players (du Toit et al., 2005).

To quantify force production in the scrum previous researchers have developed instrumented scrummaging ergometers (Quarrie & Wilson, 2000; Wu et al., 2007; Preatoni et al., 2012; 2013;). Quarrie and Wilson (2000) showed with their custom device the importance of anthropometry, physical performance and body positions in the development of total scrum force. Wu and colleagues (2007) identified the importance of individual scrum force and the kinematics of the individual player's technique. The underlying relationships between body kinematics and scrum force production may prove to be paramount to the development and optimization of individual scrum performance. Quarrie and Wilson (2000) and Wu and colleagues (2007) looked at the individual contributions and individual kinematics of scrum force development respectively. The result from these studies would suggest that improvement in the individual performances could positively influence the outcomes of the entire scrum. By isolating and recording individual scrum performance the improvement thereof may benefit the combined team performance.

More recently Preatoni et al. (2012) developed an instrumented scrum machine that was able to measure the kinetics of the entire scrum and have since used it to identify, amongst other things, the forces of team scrummaging at various competitive levels (Preatoni et al., 2013). While the magnitude of the resultant force derived from the entire scrum is essential, the direction of force application is important to player safety and scrum success (Preatoni et al., 2013).

Since player safety is paramount to the longevity of the players' careers and ultimately the game, many recent studies have been focussed on improving player safety at the scrum (Brown et al., 2013; Hendricks et al., 2014; Taylor et al., 2014; Trewartha et al., 2015). In summary scrums account for approximately 33% of all catastrophic rugby injuries (Hendricks et al., 2014). Brown et al. (2013) and Taylor et al. (2014) mentioned that the front row is at greatest risk of sustaining a scrum related injury. Current data suggests that most scrum related injuries are as a result of the scrum engagement impact followed by scrums collapsing and finally by players popping-out of formation, as a result of the forces [Hendricks et al., 2014]. Being a set phase within the game, a scrum is far more controllable than open play contacts (tackles, mauls and rucks) (Brown et al., 2013; Hendricks et al., 2014; Taylor et al., 2014; Trewartha et al., 2015) and therefore it should be possible to define the roles of players in a manner that minimises the likelihood of injury. For this reason, a better understanding of the demands in scrum is required. One facet that has been overlooked is the centre of pressure (CoP) during scrummaging.

The CoP being the position where the total force magnitude is applied to a surface or body is an established and useful variable in biomechanics (Ruhe et al., 2010) and sports science (Noe & Paillard, 2005; Murphy et al., 2009; Ball & Best, 2012). While many studies have examined the components of scrum force (Quarrie & Wilson, 2000; du Toit et al., 2004; 2005; Preatoni et al., 2013; 2014; Cazzola et al., 2014) the movement of the CoP elicited

during scrummaging in a forward direction, a measurement of the vector through which force is applied, has not yet been studied. By identifying group and individual scrummaging CoPs a player or team could work to maximise summation of forces from different elements of the scrum or alter CoP position to attack the opponent's weaker area. The mismatch between opposing teams CoP could result in an advantage at the scrum. Therefore the identification of scrum force CoP is likely to be very useful to further understanding the kinetics of the scrum. Additionally the CoP could be used to identify weaknesses in scrummaging technique and used to reduce the likelihood of injuries.

Furthermore the CoP and force magnitude can be very helpful to drive computer simulation analysis using in-vivo measurements. Additionally, the individual contributions of the scrummaging players can be useful to coaches, assisting them with talent identification and performance optimisation; while technical aspects of individual scrummaging could assist players and medical personnel in injury prevention and rehabilitation.

Aim

To contribute to the understanding of the dynamics of scrummaging, the current study aimed to instrument an individual scrummaging ergometer to allow for the measurement of individual compressive scrummaging force and the CoP. A second aim of this study was to compare the individual scrummaging force magnitudes and CoP data between different playing positions in the rugby scrum. It was hypothesised that differences in individual scrummaging force magnitudes and CoP positions would be present between the different groups of scrummaging individuals. Additionally back row forwards are expected to have more erratic CoP movement than locks and front rows.

Methods

Design and calibration of scrum ergometer

The design and construction of a custom device was necessary for measuring the CoP developed from an individual scrum engagement. This approach was adapted from a similar device developed for the measurement of the movement of the CoP during rowing (Murphy et al., 2009). The pushing surface of the scrum machine consisted of a cushioned frame which was connected to the support structure of the ergometer by four monodimensional S-type load cells (Tedea-Huntleigh type 615, Tedea-Huntleigh, Malvern, USA) fixed at each corner (Figure 6.1). This arrangement allowed for the total compressive force (F_{total}) to the scrummaging surface to be determined (sum of all four load cells: F_1–F_4), as well as the localisation of the CoP of the compressive forces. The horizontal CoP coordinate position (as referenced to the vertical axis between load cells F_1 and F_4), x_{est1}, was estimated as follows:

$$x_{est1} = \frac{x_1(F_1+F_2)}{F_{total}} \quad (1)$$

where x_1 is the mean horizontal distance between load cells (between load cells F_2 and F_3 and the distance between load cells F_1 and F_4); F_1 and F_2 are the recorded forces on each of the load cells F_1 and F_2 and F_{total} is the sum of all four load cell recordings (see Figure 6.1). A second estimation of the horizontal CoP coordinate position, x_{est2}, was calculated using the opposite side of the scrum force plate as the fulcrum.

$$x_{est2} = x_1 - \frac{x_1(F_3+F_4)}{F_{total}} \quad (2)$$

where F_3 and F_4 are the recorded forces on each of the independent load cells on the opposite side to the first estimate. The average of the two estimates was used to calculate the horizontal CoP coordinate position, *x*

$$x = \frac{x_{est1}+x_{est2}}{2} \quad (3)$$

Similarly, the vertical CoP coordinate position, y_{est1}, was estimated

$$y_{est1} = \frac{y_1(F_1+F_4)}{F_{total}} \quad (4)$$

where y_1 is the mean vertical distance between load cells (between load cells F_3 and F_4 and the distance between load cells F_1 and F_2); F_1 and F_4 are the recorded forces on each of the load cells and F_{total} is the sum of all four load cell recordings. The vertical CoP coordinate position, y_{est2}, was estimated a second time using the opposite side of the scrum force plate as the supporting point.

$$y_{est2} = y_1 - \frac{y_1(F_2+F_3)}{F_{total}} \quad (5)$$

where F_2 and F_3 are the recorded forces on each of the load cells on the opposite side of the scrum force plate as the fulcrum. The vertical CoP coordinate position, y, was calculated as the average of the two estimates

$$y = \frac{y_{est1}+y_{est2}}{2} \quad (6)$$

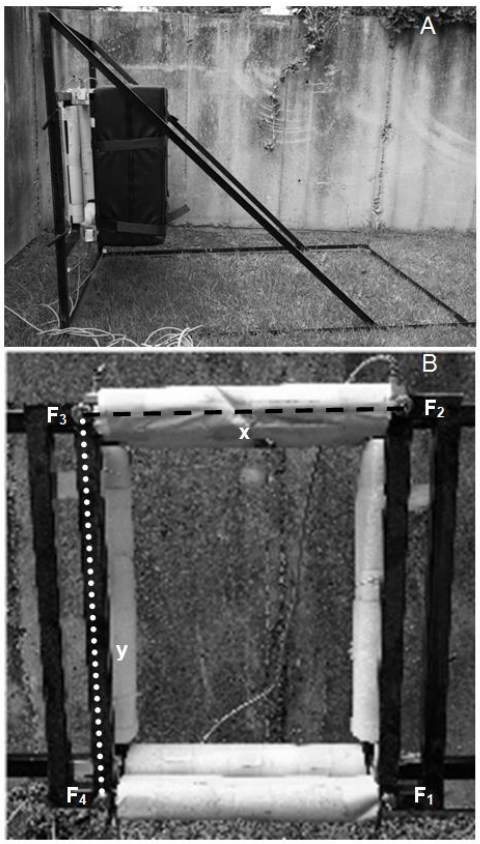


Figure 6.1: The individual scrum ergometer. A profile of ergometer with cushion pads on the scrum plate: load cells placed between support structure and scrum plate. B: Scrum plate without cushion pads: load cells positioned and F_1-F_4.

The electrical signals from the individual load cells were digitised through a signal conditioning unit (Instrunet i555, GW Instruments, Inc., Charlestown, USA) and digitally recorded. All processing of the raw digital signals was conducted in MatLab 7 (Mathworks, Mathworks, Inc., Natick, USA). Data was sampled at 160 Hz and a moving average of 10 frames was used to filter the digital signal from each load cell.

The ability of the ergometer to reliably measure applied load (the total force applied-F_{total}), relied on factory calibration of the load cells and was verified in the following way. The total mass was calculated as the sum of all four load cells filtered signals. The calculation of the force was that of the individual mass reading from each load cell multiplied by the

gravitational constant. The device was calibrated by loading and unloading weights of known mass onto the device. These tests were repeated three times on separate occasions. The cushioning pads were removed for the device calibration.

The position of the applied force was validated using a linear vertical weighted point. The design of the linear vertical mass assembly was adapted from Hall and colleagues (1996) and Murphy and colleagues (2009). Minor alterations were made to allow for a second linear bearing to be added, increasing the stability of the support of the applied mass to allow for greater masses to be applied to the scrummaging machine while ensuring a vertical motion (Figure 6.2). The spike was sharpened at the point of application to a sub-millimetre width. A one-inch-thick Perspex board was fixed to the surface of the scrummaging plate to calibrate and test the accuracy of the measurement system as described hereafter. The first position calibration trial consisted of placing a 120kg mass onto 99 predetermined locations (an 11 by 9-point grid spaced five cm apart and covering 2475cm^2).

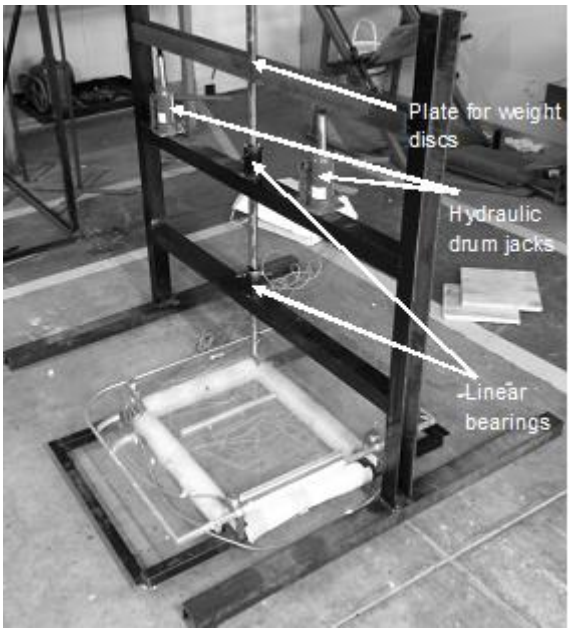


Figure 6.2: Linear vertical mass assembly used to calibrate the centre of pressure position.

In vivo machine scrummaging test

Thirty-nine amateur club players (Age: 20-34 years, body mass 101.0 ± 14.1kg) volunteered to individually scrum against the calibrated scrummaging ergometer. Ethical clearance for this study was approved by the institution's Medical Human Research Ethics Committee (clearance: M131019) Written informed consent was obtained prior to testing. The scrum machine was fixed to an outdoor brick retaining wall, with the same grass covering as is found on a rugby field. For the purpose of this study front row forwards (props and hookers; n=22) were combined into one group (body mass 107.6 ± 14.5kg); the flanks and number eights were grouped as back row players (n=6) (body mass 86.9 ± 12.2kg) and the locks were grouped together (n=11) (body mass 95.6 ± 8.5kg).

Prior to testing all participants were allowed to warm-up in their own accustomed manner, and further by practicing on the ergometer under experimental conditions. Participants wore their own rugby boots. All participants were instructed to scrum according to the call crouch-bind-set, given by a coach, in an attempt to reduce the impact and the velocity of the engagement. During the individual scrum trial, they were encouraged to keep their posture and attempt to produce maximal force. Participants chose their vertical and horizontal positions based on their warm-up trials. The participants were simply instructed to produce maximal force and maintain good posture. They individually scrummed for six seconds, repeated a maximum of two times. Their best trial (the one with maximal force) was analysed.

Data collection

From the data collected for each individual scrummaging trial the magnitude of the applied force along with the tracking of CoP movement were recorded. CoP positions are reported as the horizontal (x) and vertical (y) positions in millimetres. The starting position (min) was

defined as the position of the force at the participant's engagement. Maximum force magnitude (max) was defined as the point at which the maximal force was achieved. The min and max horizontal and vertical CoP were the CoP positions along the horizontal and vertical axes when the initial contact between the participant and the scrum ergometer was made and when the maximal force magnitude was achieved, respectively. A characteristic example (as measured for all subjects) of the force exerted and the centre of pressure tracing for a single individual is shown in Figure 6.3. The standard deviation of the CoP, was calculated from the initial contact of the participant to the ergometer to the maximum achieved force. The vertical and horizontal CoP displacements were defined as the scalar displacement from the initial CoP initial contact of the participant to the ergometer to the CoP position of the maximal force. Similarly the average CoP displacement was the mean of the CoP displacement throughout the production of the force, from the initial point of engagement to the position of maximum achieved force.

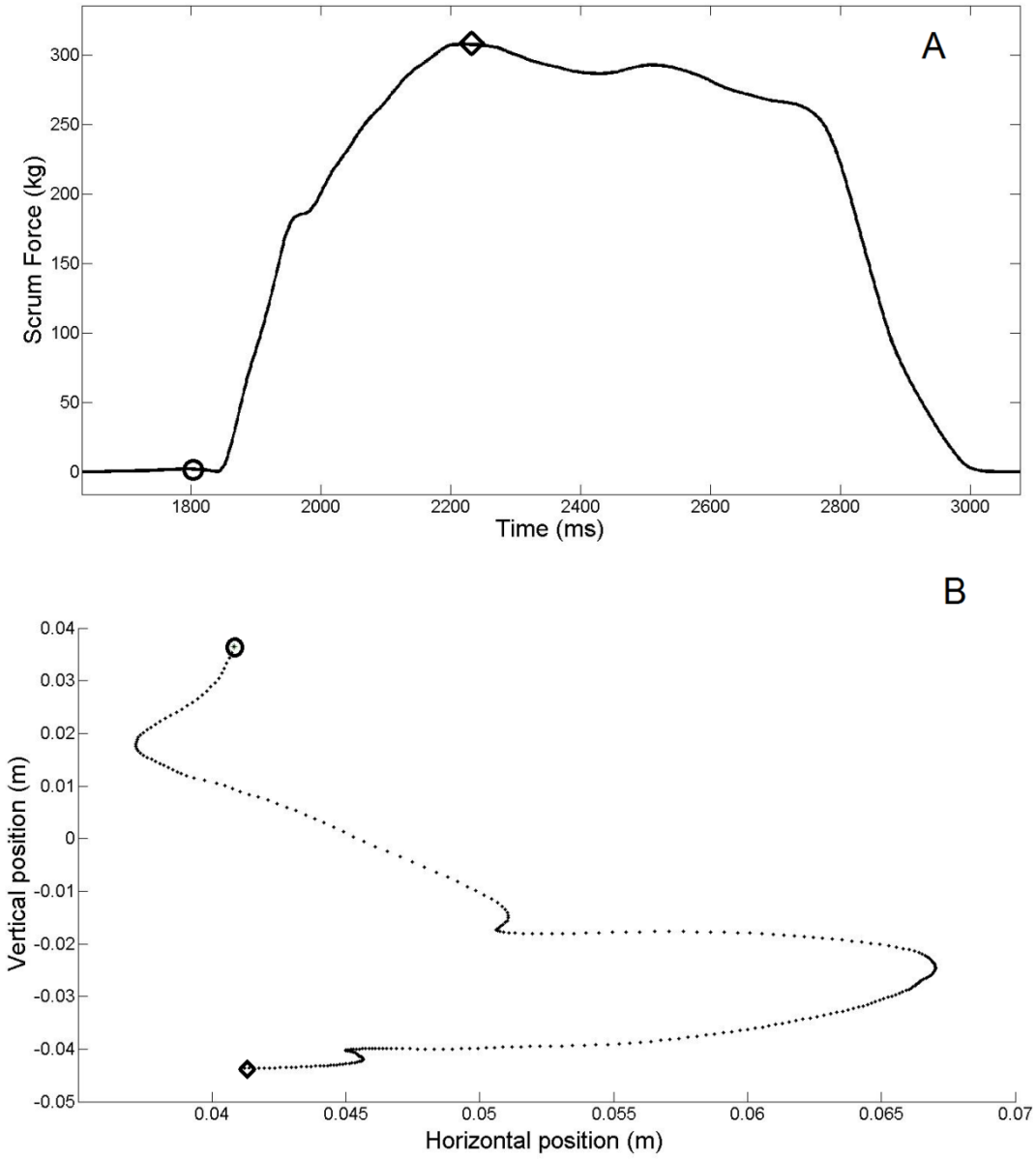


Figure 6.3: A sample tracing of the applied force (A) along with the corresponding centre of pressure (B) for a single participant (the scrummaging force was read to the participants as kilograms). The diamond indicates the starting position of the force and the circle indicates the maximum applied force.

Statistics

A one-way ANOVA was used to determine any differences between the groups of front rows, locks and back rows for each variable (Tables 6.1 and 6.2). A Bonferroni post-hoc test was used to correct for multiple comparisons when difference between individual subject groups were compared. A Pearson's correlation was used to test the relationship between maximum force produced and body weight. Confidence interval (CI) ranges are reported within parenthesis. A Bland-Altman approach was used to assess the limits of agreement between measure scrummaging loads and actual forces applied to the ergometer.

Results

Scrum ergometer instrumentation

The results loading and unloading tests (shown in Figure 6.4A) indicate that the measured mass is equal to the actual mass to within 99.99% of that placed on the surface supported by the load cells. The Bland-Altman results (Figure 6.4B) show that the error difference between actual force and measured forces are within 16.6N (maximum limit of agreement).

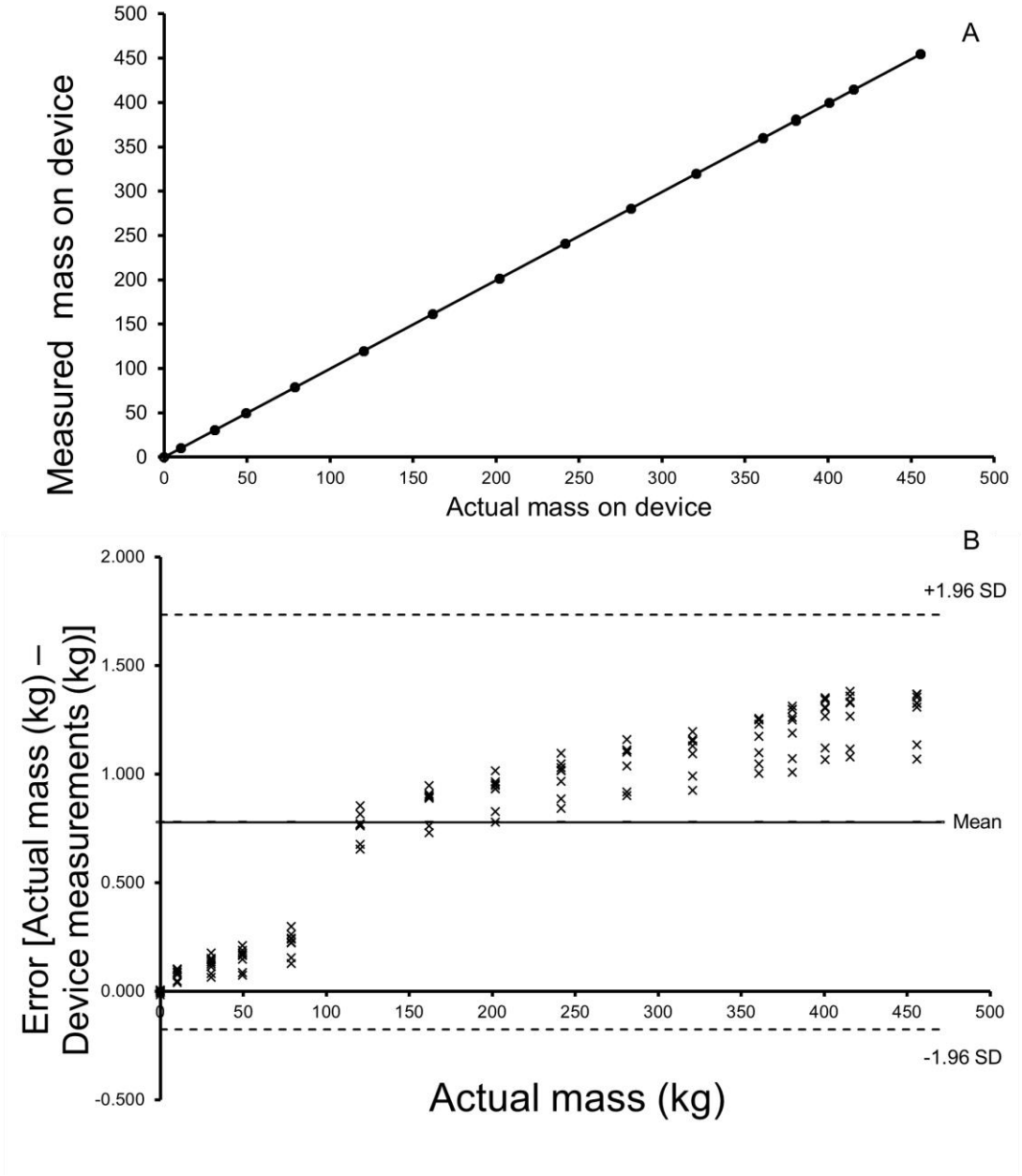


Figure 6.4: The relationship between actual force application and measured forces on the scrumming ergometer (A) and Bland-Altman Limits of agreement as a function of actual masses applied (B) for 8 trials.

A characteristic radial distortion was found when assessing the error of CoP location determination (Figure 6.5). The average error for the 99 points was recorded at 26.2 ± 14.5mm in the horizontal direction and 36.6 ± 23.9mm in the vertical direction. These data were then used to map the distortion pattern inherent to the board which were quantified

using fifth order polynomial equations. The resulting distortion correction pattern was used to calibrate the system for all subsequent data analysis. Following the calibration, the accuracy of measurement system was tested in six additional position trials, three using 80kg and another three using 120kg. No significant difference was observed in the error between the two masses (p=0.827). The resultant accuracy of estimation of determining the location of force application was quantified as 1.3 ± 0.9mm horizontally and 1.5 ± 1.2mm vertically. This equates to an improvement of 93.6% and 95.4% in the horizontal and vertical directions. A conservative estimation of the maximal measurement error of the force application location is therefore 3.2mm and 3.9mm along the horizontal and vertical axes respectively (assuming maximal error to be two standard deviations in either direction).

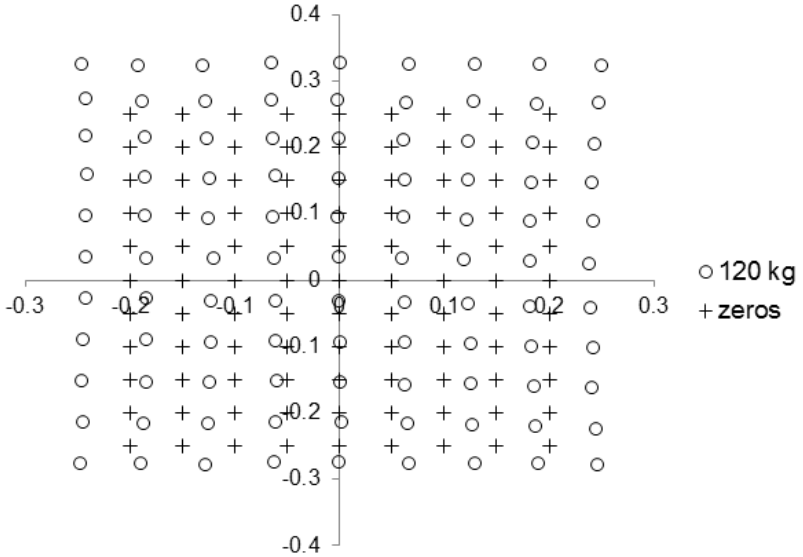


Figure 6.5: The average error of known positions compared to the calculated positions. Plus signs indicate the 99 known positions. Open circles represent vertical loading mass of 120 kg.

In vivo machine scrummaging

The body masses of players varied with playing position, with front row players being heavier than locks (CI 0.165:23.8) and back rows (CI 5.95:35.4) (p=0.0018). However there was no mass difference between the locks and back rows. There were no differences in maximum sustained force and percentage force per body mass between the groups (Table 6.1). The groups did not differ in the amount of individual compressive force they could apply (p=0.143) even when made relative to body weight (p=0.680). However, a significant correlation between the maximum sustained force and body weight was evident (r=0.510, p=0.001; n=39; CI 0.232:0.711).

Table 6.1: Scrummaging forces for 39 rugby union club players, grouped into playing positions.

	n	Maximum sustained force (N)	Force/body weight
Combined	39	2253.6 ± 649.0	2.3 ± 0.6
Front rows	22	2404.0 ± 650.3	2.3 ± 0.5
Locks	11	2185.6 ± 568.9	2.3 ± 0.6
Back rows	6	1826.9 ± 670.2	2.1 ± 0.6

There were no differences in the min horizontal CoP (p=0.070) of force application but the min vertical CoP was significantly higher for front rows than back rows (p=0.009; CI 0.038:0.288) (Figure 6.6A). The front rows had a higher max vertical CoP to the locks (p=0.015; CI 0.003:0.970) (Figure 6.6B) and lower average CoP during the individual scrum trials compared to the back rows (p=0.028; CI 0.004:0.132) (Figure 6.6C). Additionally, the front rows displayed a lower standard deviation of the vertical CoP compared to the locks

(p=0.044; CI -0.048:-0.001) (Figure 6.6D). No significant differences were observed in the horizontal CoP displacements between the three groups (Table 6.2).

Table 6.2: Positions of applied forces from three groups of rugby forwards (n=39).

Position groups (sample size)	Minimum horizontal CoP (mm)	Minimum vertical CoP (mm)	Maximum horizontal CoP (mm)	Maximum vertical CoP (mm)	Average horizontal CoP (mm)	Average vertical CoP (mm)	Standard deviation of CoP (mm)	Standard deviation of CoP (mm)
Front rows (22)	-38.9±174.0	-22.1±92.7	-10.0±43.4	-81.5±58.8	-1.1±42.4	-62.2±57.6	29.0±17.6	32.8±22.3
Locks (11)	-13.5±146.8	-59.9±108.6	17.4±36.4	-131.5±32.2	3.0±48.4	-80.7±47.3	49.5±37.3	57.4±31.7
Back rows (6)	-223.1±329.4	-185.6±157.6	-31.3±66.9	-132.4±44.0	-40.8±72.0	-130.0±59.1	36.4±22.8	36.4±26.2

All values are relative to the centre of the ergometer. The centre of the ergometer is 900mm above the surface of the ground.

Negative values in the horizontal are positions to the left of centre and below the centre in the vertical.

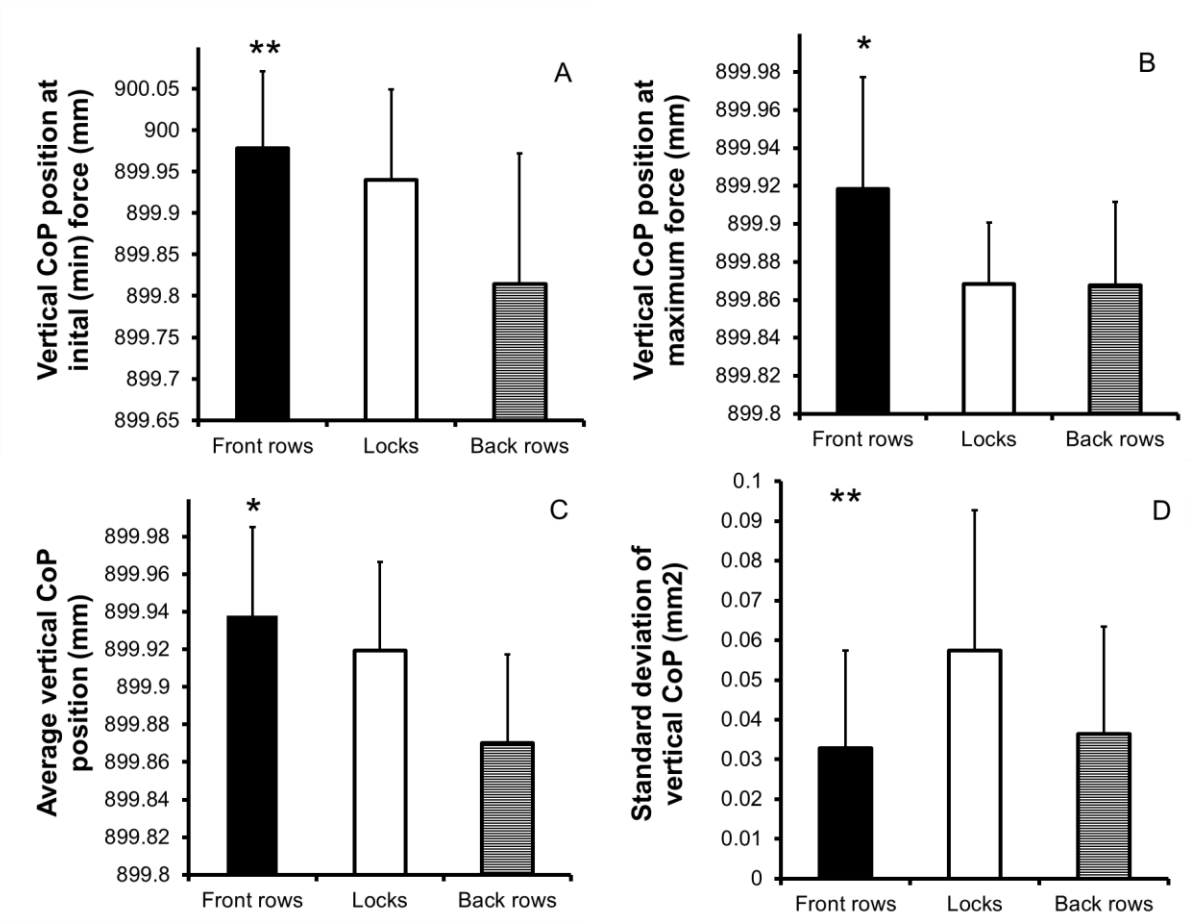


Figure 6.6: The differences between the vertical centre of pressure (CoP) between three groups of rugby forwards (n=39). A: Vertical CoP position at starting position (min). B: Vertical CoP position at maximum force (max). C: Average vertical CoP position of applied force. D: Standard deviation of the vertical position of the applied force.* Front row individuals significantly different to back rows ($p<0.05$). ** Front row individuals significantly different to locks ($p<0.05$).

Front rows moved a smaller distance to achieve their maximal force than the locks ($p=0.020$) (Figure 6.7A). Additionally, front rows moved less overall during the individual scrum trial compared to the back rows as indicated by the average CoP displacement ($p=0.028$; CI -0.120:-0.007) (Figure 6.7B).

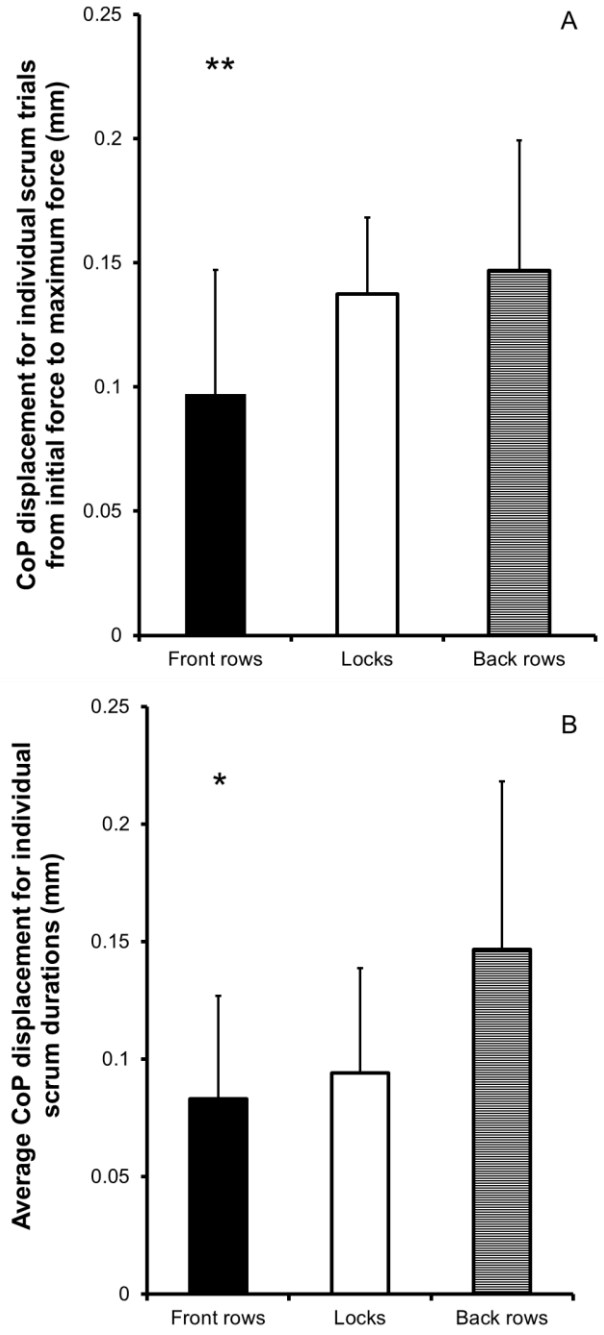


Figure 6.7: The differences between A: Displacement of the Centre of Pressure (CoP) position from centre of ergometer to the position of maximum force and B: The average CoP displacement from the centre of the ergometer for the duration of the individual scrum trials for three groups of rugby forwards (n=39). * Front row individuals significantly different to back rows ($p<0.05$). ** Front row individuals significantly different to locks ($p<0.05$).

Discussion

The current investigation aimed to instrument a force sensitive scrummaging ergometer, which enabled the measurement of the compressive magnitude and the CoP of individual scrummaging forces. The scrummaging ergometer was used to assess the scrummaging kinetics of club level rugby forward players, with inherent errors of less than 4mm for the measurement of the location of scrummaging CoP and negligible error (less than 17N) in the measurement of force magnitude. Differences between the starting and max vertical CoP, standard deviation of the CoP, and the scalar distance of the CoP were present between the groups.

Individual scrum force

The individual forces produced in this study are larger than those reported by Wu et al. (2007). The participants in the Wu et al. (2007) study recorded an average individual scrummaging force of 1067.68N±227N, which is less than half of the individual force reported in the current study. The participants in the current study performed the procedure on a grassy field similar to the conditions present during a game and were able to wear their boots unlike the indoor study by Wu and colleagues (2007). We believe that the interaction between the ground surface and the studs of the rugby boot would account for the greater force generation in the present study. Various studies have identified the interaction between the playing surface and the overall kinetic and kinematic effects (Milburn & Barry, 1998). Specifically, Queen and colleagues (2008) reported foot pressure forces differences when cleats with various stud design were used on synthetic turf. Additionally Swaminathan and colleagues (2016) tested spine kinematics in live scrummaging on different surface types, and reported improved scrum stability on modern synthetic turf compared to natural turfs.

It has been reported that the average size of rugby players has increased in recent years (Quarrie & Hopkins, 2007). The relationship between body weight and the maximal exerted force (as evident in this study) may suggest that the increase in player size over time has resulted in increases in the forces generated in the scrum (Quarrie & Wilson, 2000). Similar correlations between engagement force and body mass have been observed (Quarrie & Wilson, 2000; du Toit et al., 2005). There was however no significant difference between the groups regarding the maximal and average exerted force in the present study. It was expected that the tight five (front row and locks) would exert more force than the back rows and that there would be a difference between the front row players and the locks. du Toit and colleagues (2004) found that the individual force magnitudes differed between all groups (front rows 46%, locks 24%, and back rows 30%). The force of engagement and the sustained force of the front row were significantly greater than the locks and back rows, and suggested that this relationship was due to the larger mass and greater speed of engagement of the props compared to the other groups (du Toit et al., 2005). The lack of difference in this study might be a result of the players scrummaging individually against the ergometer and not as a combined unit of eight players. Quarrie and Wilson (2000) demonstrated that while a moderate relationship between individual scrum performance and team scrum performance exists, the sum of individuals' forces was greater than that of a combined team.

Force magnitude and Centre of Pressure

It is also important to determine the position of the generated force, both at the start of the scrum and at maximum force. du Toit and colleagues (2004) suggested that the front row make a deliberate effort to scrum higher up so as not to collapse the scrum. No differences were observed in the starting height as players were individually tested at their own freely chosen scrummaging heights. It is expected that locks and back rows would start scrummaging at a lower level than the front row, especially as a unit however this difference

was not demonstrated. The lack of starting height CoP difference could be attributed to the testing of individual scrummaging performance and not team performance. du Toit et al. (2004) mentions that the front row requires vertical stability before being able to apply force, which explains the differences that were found between their vertical force components between the three groups. While no difference between the groups with respect to their initial scrummaging CoP heights was found, a significant difference was present between the front row and locks when they achieved maximum force. The front rows were able to apply their maximal force at a higher position than the locks. Wu et al. (2007) showed that increasing pushing force could be achieved as the scrum height was increased, with the greatest force occurring at 40% of the participants' height. In addition to this, our data shows that the front row managed to stay within a smaller vertical range and have less movement of their force than locks. These variables would indicate that the front row players manage to achieve a maximal force at a similar position to their starting positions, while the locks tend to shift around their centre of pressure to a greater extent while achieving their maximal force. These results show the importance of the front row engagement technique resulting from the rules governing the scrum. A similar difference is seen between the front row and the back rows, with the front row having a lower average vertical movement in the centre of pressure and overall force movement. du Toit and colleagues (2004) showed that the front rows' vertical force component was greater than both locks and back rows; likewise locks had a greater vertical force component than the back rows. Both of these findings would suggest that front row players tend to apply their forces upwards, during sustained scrummaging when performed as a unit. This may be further compounded by the addition of the locks and back rows to the scrum, as any additional force added from behind would affect the postures of front row players. The contribution of the locks' forces and the effects of their binding position on the front row necessitates further investigation.

The importance of the lateral forces should not be overlooked in the scrum. Preatoni and colleagues (2013) showed that the lateral forces produced in the scrum are directed in a clockwise manner (towards the opposing tight-head prop). du Toit et al. (2004) showed that the horizontal force during the sustained force was greater in the front rows compared to the other two other groups. Similarly the difference was present between locks and back rows (du Toit et al., 2004); however this difference may be a knock on effect from the props as the two effects are not mutually exclusive. It is likely that back rows, in particular, will have a greater lateral component to their maximal forces when scrummaging as a unit than individually (du Toit et al., 2005). The primary purpose of the back rows in the scrum is to keep the tight five as close to each other as possible all the while adding to the magnitude of the resultant forward force. This would mean that the flanks on either side of the scrum would push on their respective front row player with a greater lateral component than a forward component (Quarrie & Wilson, 2000). While the comparison between the horizontal CoP, measured in the current study, and the lateral component vector, measured in the latter studies, are not mutually exclusive; one could infer a relationship between the two variables. However no differences were found between the CoP locations and the three groups in the current study. This result is in contrast to the original hypothesis that back rows would have a greater horizontal shift in their CoP compared to front rows and locks.

The current study showed the development of an individual scrum ergometer that has the capability of measuring the compressive scrum force magnitude and centre of pressure movement with considerable accuracy. The higher application and smaller variation in force point of application found within the front rows in the present study, raises interesting subsequent questions. Firstly, how pushing forces of scrummaging individuals may alter the posture of those around them and considerably alter the dynamics of the collective scrum? Secondly, how the height and position of the individual forces may affect the overall

magnitude of the scrum force? And lastly, how the individual movement of the players would affect their contributions to the overall scrum?

Limitations:

The results in the current study display how individuals within the different position in the scrum have differences in CoP application. The results may not be applicable to a team environment as the addition of team mates and different scrum binding strategies may affect the overall team CoP. Additionally, the assessment of an individual may not reflect the player's performance when in the team's scrum. In fact, an individual's performance may be impeded by the addition of other players in the team scrum (Milburn, 1993). Moreover, the effects may not translate from machine scrummaging, tested in this study, to live scrummaging between two teams. Further investigation into the CoP of an entire eight-person team scrum is required. Another limitation of the current study is the within-subject variability. The one trial selected for each subject (being the one with maximal force) would test the limits of the ergometer. However the within-subject could play a role between the groups and could potentially identify superior scrummaging players. This characteristic warrants further research. Regarding the instrumentation of the ergometer, cushioning pads were removed for the device calibration. However the effect of the cushions may have slightly reduced the total compressive force and the impulse measurement of the engage force.

Conclusion

The design of a single person scrum ergometer has enabled the measurement of differences in individual scrum force CoP heights and directional variation in front row players compared to their scrummaging counterparts. The application of this/similar ergometers may allow

coaches and player to optimise the application of forces through technical improvements in their teams.

References

Ball, K. & Best, R. (2012). Centre of pressure patterns in the golf swing: individual-based analysis. *Sports Biomechanics*, 11(2): 175-189.

Brown, J.C., Lambert, M.I., Verhagen, E., Readhead, C., van Mechelen, W. & Viljoen, W. (2013). The incidence of rugby related catastrophic injuries (including cardiac events) in South Africa from 2008 to 2011: a cohort study. *British Medical Journal Open* 3: e002475. doi:10.1136/ bmjopen-2012-002475.

Cazzola, D., Preatoni, E., Stokes, K., England, M.E. & Trewartha, G. (2014). A modified prebind engagement process reduces biomechanical loading on front row players during scrummaging: a cross-sectional study of 11 elite teams. *British Journal of Sports Medicine,*1-6. doi:10.1136/bjsports-2013-092904.

du Toit, D.E., Venter, D.J.L., Buys, F.J. & Olivier, P.E. (2004). Kinetics of rugby union scrummaging in under-19 schoolboy rugby forwards. *South African Journal for Research in Sport, Physical Education and Recreation*, 26: 33-50.

du Toit, D.E., Olivier, P.E. & Buys, F.J. (2005). Kinetics of full scrum and staggered scrum engagement in under-19 schoolboy rugby union players. *South African Journal for Research in Sport, Physical Education and Recreation,* 27: 15-28.

Hall, M.G., Fleming, H.E., Dolan, M.J., Millbank, S.F. & Paul, J.P. (1996). Static in situ calibration of force plates. *Journal of Biomechanics*, 29(5): 659-665.

Hendricks, S., Lambert, M.I., Brown, J.C., Readhead, C. & Viljoen, W. (2014). An evidence-driven approach to scrum law modifications in amateur rugby played in South Africa. *British Journal of Sports Medicine*, 48: 1115-1119.

Milburn, P.D. (1993). Biomechanics of Rugby Union Scrummaging: Technical and safety issues. *Sports Medicine,* 16(3): 168-179.

Milburn, P.D. & Barry, E.B. (1998). Shoe-surface interaction and the reduction of injury in rugby union. *Sports Medicine*, 25: 319-327.

Murphy, A.J., Chee, S.T.H., Bull, A.M.J, & McGregor, A.H. (2009). The calibration and application of a force-measuring apparatus on the seat of a rowing ergometer. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and* Technology, 224(1): 109-116.

Noé, F. & Paillard, T. (2005) Is postural control affected by expertise in alpine skiing? *British Journal of Sports Medicine,* 39: 835–837.

Preatoni, E., Wallbaum, A., Gathercole, N., Coombes, S., Stokes, K.A. & Trewartha, G. (2012). An integrated measurement system for analysing impact biomechanics in the rugby scrum. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology,* 226: 266–273.

Preatoni, E., Stokes, K.A., England, M.E. & Trewartha, G. (2013). The influence of playing level on the biomechanical demands experienced by rugby union forwards during machine scrummaging. *Scandinavian Journal of Medicine and Science in Sports,* 23: e178-184.

Preatoni, E., Stokes, K.A., England, M.E. & Trewartha, G. (2014). Engagement techniques and playing level impact the biomechanical demands on rugby forwards during machine-based scrummaging. *British Journal of Sports Medicine,* 49(8): 520-528.

Quarrie, K.L. & Wilson, B.D. (2000). Force production in the rugby union scrum. *Journal of Sports Sciences,* 18: 237-246.

Quarrie, K.L. & Hopkins, W.G. (2007). Changes in player characteristics and match activities in Bledisloe Cup rugby union from 1972 to 2004. *Journal of Sports Sciences*, 25(8): 895-903.

Queen, R.M., Charnock, B.L., Garrett, W.E., Hardaker, W.M., Sims, E.L. & Moorman, C.T. (2008). A comparison of cleat types during two football-specific tasks on FieldTurf. *British Journal of Sports Medicine*, 42: 278-284.

Ruhe, A., Fejer, R. & Walker, B. (2010). The test–retest reliability of centre of pressure measures in bipedal static task conditions – A systematic review of the literature. *Gait & Posture*, 32: 436–445.

Swaminathan, R., Williams, J.M., Jones, M.D. & Theobald, P.S. (2016). A kinematic analysis of the spine during rugby scrummaging on natural and synthetic turfs. *Journal of Sports Sciences*, 34(11): 1058-1066.

Taylor, A.E., Kemp, S., Trewartha, G. & Stokes, K.A. (2014) Scrum injury risk in English professional rugby union. *British Journal of Sports Medicine*, 48: 1066–1068.

Trewartha, G., Preatoni, E., England, M.E. & Stokes, K.A. (2015). Injury and biomechanical perspectives on the rugby scrum: a review of the literature. *British Journal of Sports Medicine*, 49: 425–433.

Wu, W.L., Chang, J.J., Wu, J.H. & Guo, L. Y. (2007). An investigation of rugby scrummaging posture and individual maximum pushing force. *Journal of Strength and Conditioning Research*, 21: 251–258.

World Rugby Rule 20.1a. Laws of the Game (Internet). http://laws.worldrugby.org/index.php?law=20. Accessed 1 March 2015.

Chapter 7:

A lower body height and wider foot stance are positively associated with the generation of individual scrummaging forces in rugby. Andrew Green, Samantha Kerr, Benita Olivier, Chloe Dafkin and Warrick McKinon. Manuscript under review at the *International Journal of Performance Analysis in Sport.*

Abstract

A scrum is a contest to win possession of the rugby ball. The current study investigated potential kinematic parameters related to individual scrummaging force production. Twenty-five 'tight-five' players (body mass: 103.0±12.1kg; height: 1.85±0.09m) individually scrummaged against an instrumented ergometer, while body kinematics were captured. Pearson's correlations between force generation and kinematics of individual scrummaging performances were performed. Body mass was correlated to the engagement (r=0.641), peak (r=0.531), and sustained (r=0.438) forces. Stance width was significantly correlated with the individual scrummaging forces at engagement (r=0.422) and sustained phases (r=0.540) but not at peak phase (r=0.369). Higher scrummaging forces were achieved at lower pelvic and back heights. The only significant relationship during the start-sustained phase was the change in pelvic height (r=-0.562). Changes in right hip (r=-0.477) and right knee (r=0.474) angles were correlated to the change in force during engagement-peak phase. During engagement-sustained phases change in force magnitude was correlated to changes in pelvic height (r=-0.585), left hip (r=0.549) and right ankle (r=0.657). The change in pelvic height (r=-0.518) was the only correlate during the peak-sustained phase. The presented data highlights the role of a lower body height and wider stance in the attainment of greater individual scrummaging force.

Introduction

The scrum was designed as a method to fairly and quickly restart a rugby game after a minor infringement has occurred (World Rugby Law 20). The scrum is a physical contest where eight players from opposing sides are involved in a coordinated push for possession of the ball. To gain an advantage in the scrum is essential to a team's performance with more than 20 scrums occurring in an average game (Fuller et al, 2007; Roberts et al, 2014). Forwards (a subdivision of the rugby team, consisting of the eight players who partake in the scrum) can expect to spend 10% of the total game time in the high intensity static competition of the scrum (Duthie et al., 2003).

The kinetics of the full eight-man scrum is normally divided into two phases: the engagement phase and the sustained force phase. The engagement phase is determined by the meeting of the opposing front rows. The combined forces during this phase can exceed 6000N (Quarrie & Wilson, 2000; Cazzola et al., 2014; Preatoni et al., 2014). The sustained force phase follows the engagement phase and is characterised by lower exerted forces ranging around 3500N (Cazzola et al., 2014) in the combined scrum. To gain scrummaging supremacy a team must produce more forward force than the opposition. Although a mismatch in force production between teams during a scrum is a major driver in scrummaging success, such a mismatch has been identified as a cause for injury concern (Brown et al., 2013; Hendricks et al., 2014; Taylor et al., 2014; Trewartha et al., 2015).

Milburn (1990) and more recently Sharp and colleagues (2013) have advocated the need for players to have a high level of functional strength to maintain the correct body posture while scrummaging. Specifically the trunk musculature has been shown to be important in the transmission of the forward force during scrummaging (Cazzola et al., 2014; Sharp et al., 2014). Whole team scrummaging forces are known to increase with playing level (Preatoni,

et al., 2013). This increase in the force across playing level is likely to be a result of better technique within the team's individual performances (Preatoni et al., 2013). The development of scrummaging forces are derived from the ground and transmitted through the shoulders between players, and eventually to the opposite team (du Toit et al., 2004). Coaching manuals suggest that scrummaging performance can be improved by lowering the total height of the scrum; and secondly, as individuals, that a wider base of support should allow for a larger force to be generated and sustained throughout the scrum duration (Noakes & du Plessis, 1996). Such an approach should theoretically aid in the generation of force by the summation of the actions of three lever arms (around the ankle, knee and hips); and the propagation of that force along the spinal axis to the shoulders.

Body positioning kinematics must play a role in the development and maintenance of scrummaging forces (Flavell et al., 2013; Wu et al., 2007). Flavell and colleagues (2013) premised that attacking scrums produce larger forces than defending scrums, and showed how the kinematics of the limbs were different with larger hip displacement during defensive compared to attacking scrums. Additionally, Wu et al. (2007) showed that body kinematics, specifically the hips, knees and ankles, are related to individual scrum performance.

While the scrum is the combined effort of all eight players the individual performance of each player is the origin of such forces. Quarrie and Wilson (2000) reported a moderate relationship between the contributions of individual scrummaging performance and the combined team performance. The individual force contributions within the team scrum are not equally distributed between the eight players. The majority of the force is generated by the front row and part of the second row, known collectively as the tight five (du Toit et al., 2004). Correct scrummaging technique and the ability of individual players to coordinate their force applications are essential to team scrummaging performance (du Toit et al., 2005)

and therefore is an important target for investigation, in the study of scrummaging performance.

The purpose of the current study was therefore to investigate the possible kinematic contributors to individual scrummaging performance in tight five players. Following from the postulate that lower body positions and kinematics may be important predictors of scrummaging forces (Rodano & Pedotti, 1988), it was hypothesised that scrummaging requires: a good base of support; and that scrummaging forces are related to joint angles of the legs and to back straightness (extension in both cases); that a lower body position would produce greater scrummaging forces; and finally that a measure of lower body power, vertical jump, is related to the generation of individual scrummaging force.

Methods

Participants

A group of twenty-five university level players consisting of props, hookers and locks volunteered to take part in this study. All participants were injury free and written informed consent was received prior to the start of testing. Ethical approval was granted by the University Ethics Committee (M131019).

Instrumentation and equipment

An individual instrumented scrum ergometer (Green et al., 2016) was used to record the individual scrummaging magnitudes. The individual scrummaging forces were recorded at 160Hz and filtered using a moving average of eight time periods.

An 18 camera system recording at 100Hz (Optitrack flex:V100r2 (Natural Point Inc., Corvallis, Oregon, USA)) was used to capture all the individual scrummaging kinematics. A recording volume was calibrated on an outdoor practice facility. Calibration and 3D tracking was performed using AMASS (C-Motion Germantown, Maryland, USA), and was reported to be sub-millimetre. Retroreflective markers were placed bilaterally on the inferior angle of the scapulae (SCAP); posterior iliac spines (PSIS); superior iliac spines (SIS); greater trochanter; mid-thigh; mid-calf; heels. Medial and lateral markers were placed bilaterally on the malleoli of the ankles and knees. Individual markers were placed bilaterally on the dorsal aspect of the feet. Markers along the back included T7; T10; L1; and L4. Custom written algorithms (described below) were used to calculate the biomechanical variables in MatLab 7 (Mathworks, Natick, Massachusetts, USA).

Procedure

All participants were allowed to warm-up in their own accustomed manner, prior to the test and further by practicing on the individual scrum ergometer under experimental conditions. Participants wore their own rugby boots. All participants were instructed to scrum according to the call crouch-bind-set, given by a coach. On the call of ‘crouch’ the participants would flex their knees and hips to get themselves into a crouched position, with their torsos near parallel to the ground and their feet parallel to one another. On the ‘bind’ call participants would reach out with their arms and grip onto the scrum ergometer within the allocated areas. They were instructed to have their ears in between the cushions of the ergometer to reduce the engagement impact. On the call of ‘set’ participants would engage the machine and attempt to produce a maximal force. The participants were allowed to adjust their foot positions during the test, as long as they did not ‘march’ their feet. Participants were verbally encouraged to produce maximal force and to maintain good scrummaging posture throughout the trial.

All participants took part in a vertical jump test to determine whether individual scrummaging force and a simple field test for lower body power were related. Participants were instructed to crouch down until their thighs were parallel with the ground. Once crouched down they were instructed to jump as high as possible. Their jump heights were obtained kinematically through tracking the position of the mid-point of the PSIS markers. The jumps were repeated twice and the average jump height was calculated.

Data reduction

The individual scrum forces were divided into six phases: starting force to engagement force (duration defined by first peak); starting force to peak force (duration defined by maximum force); starting force to sustained force (duration following peak force to the end of the phase); engagement force to peak force (duration defined between first peak and maximal peak); engagement force to sustained force (duration defined between first peak and end of sustained phase); and peak force to sustained force (duration defined between maximal peak and end of sustained phase) (Figure 7.1).

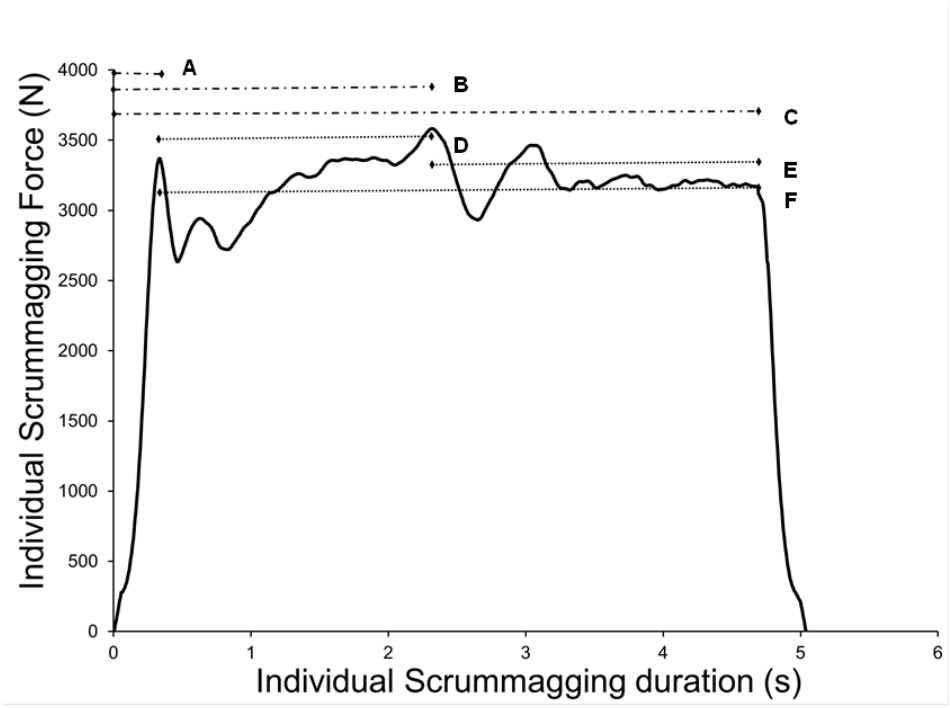


Figure 7.1: Individual scrummaging force tracing and the duration divisions: A starting force to engagement force; B starting force to peak force; C starting force to sustained force; D engagement force to peak force; E engagement force to sustained force; and F peak force to sustained force.

The bilateral angles of the hips were calculated as the angle between back vector (mid scapulae to mid hip joint centre) and the femur vector (hip joint centre to knee joint centre). Bilateral knee and ankle flexions were calculated as the angle of flexion between femur vector and the vector of the shank (knee joint centre to ankle joint centre), and the angle of flexion between the vector of the shank and the foot (ankle joint centre to toe), respectively. Back extension angle was calculated between the upper back (mid-point of the SCAP to T10) and lower back (T10 to mid-point of the PSIS) and indicates the straightness of the back, when assess in the sagittal plane. Angles of 180° indicated full extension of the back, hip and knee, respectively. The stance width was calculated as the distance between the ankle joint centres (Figure 7.2). The pelvic and back heights were calculated as the position of the mid-

point of the PSIS and the mid-point of the SCAP divided by the standing height of the participant.

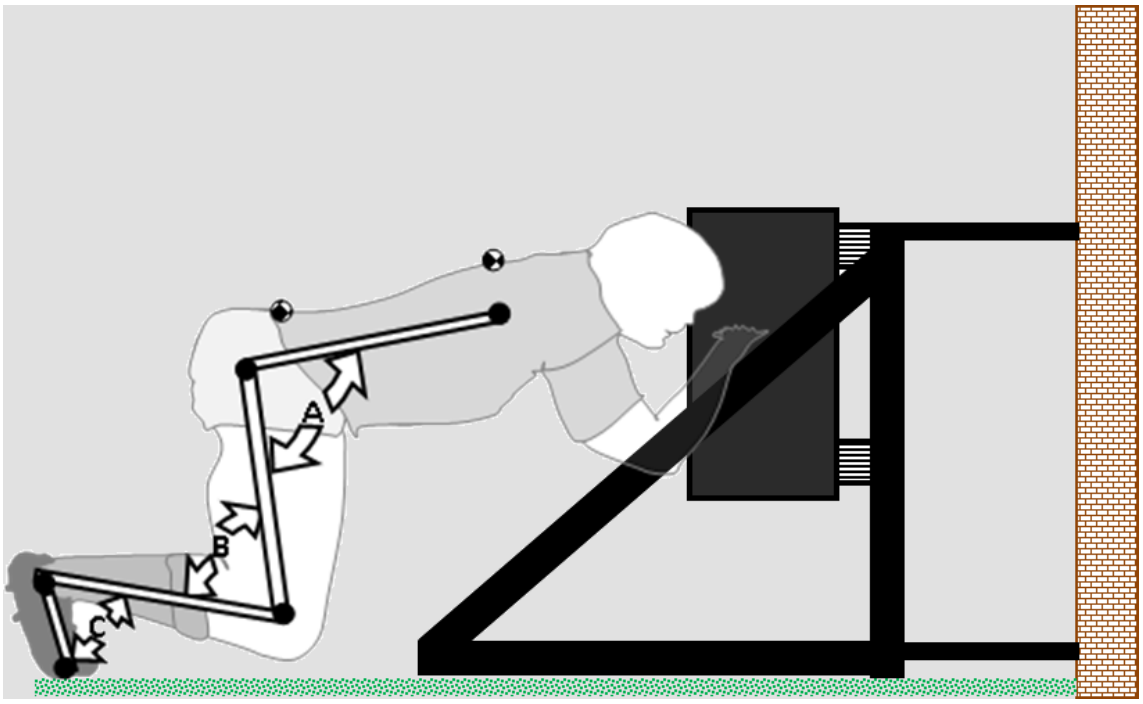


Figure 7.2: Definitions of kinematics variables in the starting position. All variables are calculated bilaterally. A. Hip extension. B. Knee flexion. C. Ankle Flexion. Stance width was calculated as the distance between the feet. Back and pelvic heights were calculated as their positional heights from the global ground plane.

Statistical analysis

The distributions of the data were tested using a Shapiro-Wilk test. All data were normally distributed and are represented as mean ± standard deviation. Pearson's correlations were performed between the kinetics and kinematics of the individual scrummaging performances. Qualitative descriptions (Portney & Watkins, 2009) for the strength of the relationships were defined as little or no relationship: $0.00<r<0.25$; fair relationship: $0.25<r<0.50$; moderate to good relationship: $0.50<r<0.75$; and good to excellent relationship: $r>0.75$. All statistical

procedures were performed in GraphPad Prism 5 (GraphPad, San Diego, California, USA). A significance level *p*-value of 0.05 was established.

Results

The combined group anthropometry results were age: 22.5±2.9 years; body mass: 103.0±12.1kg; and height: 1.85±0.09m.

The average engagement force was 1826±452N; the average peak force was 2458±455N; and the average sustained force for the individual scrummaging tests was 1700±696N. Significant correlations were present between body mass and the engagement (r=0.641; *P*=0.001); peak (r=0.531; *P*=0.006) and sustained (r=0.438; *P*=0.029) forces.

The average vertical jump height was 0.45±0.11m. No significant correlations were present between the vertical jump height and the engagement (r=-0.071, *P*=0.738), peak (r=0.084, *P*=0.691) or sustained (r=-0.072, *P*=0.734) forces.

Table 7.1: Mean and standard deviation kinematic values for individual scrummaging performance at the start, engagement, peak force and sustained force phases (n=25).

Kinematic parameters	Corresponding scrum force positions			
	Start	Engagement	Peak	Sustained
Right hip extension angle (°)	114.1±25.8	137.9±23.3	155.0±15.9	155.7±19.6
Left hip extension angle (°)	114.3±27.5	134.0±20.6	152.6±17.4	149.9±20.5
Right knee flexion angle (°)	69.4±20.9	52.1±19.1	35.0±14.3	35.5±23.9
Left knee flexion angle (°)	66.4±22.9	51.1±16.8	37.6±17.1	31.35±17.0
Right ankle angle (°)	75.1±13.5	73.7±13.5	74.6±13.8	78.6±19.8
Left ankle angle (°)	72.4±19.6	73.1±17.2	70.5±18.8	76.9±20.4
Back extension angle (°)	166.9±6.7	169.2±5.9	168.7±5.6	167.0±5.5
Stance width (m)	0.4±0.1	0.4±0.2	0.4±0.2	0.4±0.2
Pelvic height (%)	42.4±5.0	42.6±4.5	41.1±5.1	41.5±5.1
Back height (%)	47.2±6.4	49.5±5.5	49.9±5.1	49.2±4.5

Pelvic and Back heights are measured as the percentage of the standing height

The individual kinematics indicates the positions at the six phases of the scrum trials (Table 7.1). In the starting position participants were crouched over with their torsos near parallel to the ground, with flexion occurring at the knees and the hips. The participants extended their knees and hips upon engagement with the individual scrum ergometer. The extension of the hips and knees continued until the peak force and these values were maintained throughout the sustained force phase. The flexions of the ankles did not undergo any major changes, remaining fairly consistent throughout the scrummaging durations (Table 7.1). Stance width remains fairly consistent throughout the scrum duration (Table 7.1).

No significant correlations were evident between force generation and angles of the hips, knees, ankles or the thigh alignments at any stage of the scrum trial (Table 7.2). The back angle had a fair relationship with the force at the sustained phase. Stance width was significantly correlated to the force produced at the engagement and the sustained force phases. These statistically significant relationships are considered to be fair and moderate to good, respectively. A larger stance width is suggested to increase the individual scrummaging force. Pelvic height percentages were significantly correlated to force generation at all three phases of the scrummaging (Table 7.2). The fair relationships at engagement and peak force phases and the moderate to good relationship at the sustained phase would suggested that a lower pelvic height is advantageous to increasing individual scrummaging forces. Similarly back height percentages were significantly correlated at all three phases of the scrummaging (Table 7.2).

Table 7.2: Correlation coefficients (Pearson's r) between force generation and bilateral hip angles, bilateral knee and ankle flexions, stance widths, pelvic height percentages, and back height percentages at the engagement, peak force and sustained force positions.

Kinematic parameters	Corresponding scrum force positions		
	Engagement	Peak	Sustained
Right hip extension angle (°)	-0.288	0.173	0.224
Left hip extension angle (°)	-0.176	0.332	0.227
Right knee flexion angle (°)	0.280	-0.275	-0.291
Left knee flexion angle (°)	0.111	0.000	-0.130
Right ankle angle (°)	0.273	-0.359	0.045
Left ankle angle (°)	0.118	0.176	0.249
Back extension angle (°)	0.064	0.086	0.444*
Stance width (m)	0.422*	0.369	0.540**
Pelvic height (%)	-0.475**	-0.412*	-0.573**
Back height (%)	-.0585**	-0.424*	-0.437**

n=25

* $P<0.05$

** $P<0.01$

Pelvic and Back heights are measured as the percentage of the standing height

No changes in the kinematic parameters were correlated to changes in force produced during the start-engagement and start-peak phases (Table 7.3). The change in the pelvic height percentage was significantly related to the change in the individual applied force from the start to the sustained phase (Table 7.3). The relationship is considered to be moderate to

good, and would indicate a reduction in the pelvic heights would increase the individual scrummaging forces. The change in forces during the engagement-peak phase were negatively correlated to the change in right hip flexion and positively correlated to the change in right knee flexion for the same phase. Both of these relationships are considered to be fair. During the engagement-sustained phase significant relationships were present for the changes in left hip flexion, right ankle flexion, percentage pelvic height and the individual force. The relationships are considered to be moderate to good during this phase of the scrummaging (Table 7.3). The only significant correlation during the peak-sustained was the change in the pelvic height percentage and the individual force.

Table 7.3: Pearson's correlation coefficients (r) for the changes in the force magnitude and the changes in body kinematics during the six phases of the individual scrummaging trials.

Change in value	Change in Force					
	Start-Engagement	Start-Peak	Start-Sustained	Engagement-Peak	Engagement-Sustained	Peak-Sustained
Right hip angle (°)	0.105	0.281	0.353	-0.477*	0.404	0.140
Left hip angle (°)	-0.031	0.210	0.267	0.020	0.549**	0.409
Right knee flexion angle (°)	0.061	-0.055	-0.177	0.474*	-0.275	0.143
Left knee flexion angle (°)	0.227	0.082	-0.061	0.182	0.010	-0.076
Right ankle angle (°)	0.303	-0.350	0.087	0.008	0.657**	0.258
Left ankle angle (°)	0.039	0.165	0.176	-0.010	0.152	0.381
Back angle (°)	0.173	0.140	0.230	0.229	0.013	-0.020
Pelvic height (%)	-0.388	-.0340	-0.562**	-0.235	-0.585**	-0.518**
Back height (%)	-0.094	0.087	-0.054	-0.383	-0.287	-0.279

n=25
* $P<0.05$
** $P<0.01$
Pelvic and Back heights are measured as the percentage of the standing height

Discussion

The purpose of this study was to investigate potential performance parameters for individual scrummaging. The first hypothesis was that scrummaging requires a good base of support. The moderate to good relationship between the stance width and the individual scrummaging forces at multiple phases during the scrum trials, support the important role of a solid base of support in scrummaging force generation. Secondly scrummaging forces were proposed to be related to the joint angles of the back and legs. However, apart from the back angle, no significant relationships at any phase during the scrum duration were present for the forces and the kinematics of the joint angles. Following from the postulate of Rodano and Pedotti (1988) and anecdotally that a lower body position when scrummaging is advantageous to produce greater scrummaging forces, the pelvic and back heights of the scrummaging player were shown to be advantageous where higher scrummaging forces were achieved at lower heights above the ground. Finally no significant relationships were obtained between the individual scrummaging forces and vertical jump heights.

Force magnitude, body mass and lower body power

Moderate to good relationships were observed between body mass and the development of force at the engagement and peak force phases. A fair relationship was observed between body mass and force development of the sustained force. du Toit et al. (2005) suggested force generated during the engagement phase is determined by the speed at which the engagement occurs and the mass of the scrummaging unit. The data presented in the current study for individual body mass and individual scrummaging force would agree with the group data presented by du Toit et al. (2005) and Quarrie and Wilson (2000). du Toit et al. (2005) reason that mass alone is not responsible for the sustainment of force during the team scrum, and that team scrummaging performance during the sustained force phase must be related to the teams' scrummaging techniques. While our data shows that a relationship exists between the

individual body mass and the individual sustained force, the relationship was only classed as ‘fair’ and therefore it is likely that other factors (not related to body mass alone) are responsible for the sustainment of the force. Individual scrummaging force is known to be related to multiple strength and power tests (Quarrie & Wilson, 2000). However there were no relationships between vertical jump height and force magnitudes shown in the current study. A similar result was reported by Quarrie and Wilson (2000). The lack of relationships between the vertical jump height and the individual scrummaging forces could imply that the lower body power used to achieve scrummaging forces are more complex than the simple vertical jump allows for and require a more in-depth analysis.

Static phase performance correlates

In the current study only the back angle was significantly correlated to the individual forces. The back angle, representing the straightness of the back, had a fair relationship with the individual force at the sustained phase. A straighter back is likely to be beneficial in assisting the transfer of the power generated by the legs to the ergometer (opponent). The remaining body kinematic parameters (hips, knees and ankles) showed no significant relationships with the individual scrummaging force. Quarrie and Wilson (2000) reported a similar result with no correlations being identified between the body kinematics and the individual forces. However Wu et al. (2007) reported significant negative correlations for the hips, knees and ankles with the individually produced scrummaging force. One particular reason for these relationships was attributed to the distance of the individuals from the scrummaging machine (Wu et al., 2007). The distance of the individuals from the ergometer in the current study was assumed to be less than those in the Wu et al. (2007) study. Our participants were instructed to have their ears in line with the shoulder cushions. Additionally the rules surrounding the scrum engagement have change since the publication of Wu et al. (2007). It is likely that the

forces produced must be a result of either the change in angle of the segments or be more complex than pure kinematics allow for.

The need for an effective base of support, allowing for greater forces to be applied to the ground (and therefore for greater scrumming force generation) was confirmed. However no significant correlation was observed at the peak force. This may be as a result of minor movements for the participants to establish their footing in order to maintain the sustained force. During a team's scrummaging trial, it is noted that there is a rebound effect (Preatoni et al., 2014). A similar effect, while not distinctly observed in the current study, may be apparent during individual scrummaging and may require the resetting of the feet, which could in turn alter stance width.

The height of the scrum was expected to affect the attainable forces. Wu et al. (2007) showed in a group of ten participants how the individual scrummaging forces were greatest when the scrum was performed at 40% of the participants' heights. Our data agree with this finding. While we did not alter the height of the ergometer, all of the participants in the current study tended to start and maintain a body position around 40% of their height for the individual scrummaging trials. The height of the pelvis and the back were significantly correlated to the individual forces at all stages (engagement, peak, and sustained) of the scrummaging trial. These relationships would suggest that a lower body position is beneficial to producing greater individual forces. This particular finding is contradictory to Wu et al. (2007) who found that forces improved from increasing the scrummaging height from 36%-40% of their participants' heights. The difference may be that an optimal scrummaging height (near to 40% of stature) exists. This requires further investigation. The body height and the force generation might be influenced by the leg kinematics and the contractile properties of the muscles.

Dynamic kinematics and kinetic correlates

Correlations were performed in an attempt to identify the specific joints responsible for the changes in force between the phases of the individual trials. No joint angle parameters analysed in this study could account for the changes in force during the start-engagement and start-peak phases. It is likely that these phases are related to the physical principles (masses, velocity) and physiological principles (force of contraction, recruitment of fibres). Similar to Quarrie and Wilson (2000) the current study reported the lack of significant relationships between vertical jump heights and scrummaging forces. This, in addition to the lack of correlation between joint angles and individual scrummaging forces, may indicate that factors other than force generation capacity and the body position employed in scrummaging are important for scrum force generation. Sharp et al. (2014) reported that scrummaging players of different levels may rely on different strategies to produce maximal forward force. It was concluded that juniors may use their mass or technical strategies to produce maximal force, while professional players utilise muscular strength, specifically the lower back to produce maximal individual force (Sharp et al., 2014). These ideas remain speculative and require additional investigation. Further studies may want to assess muscle strength and contractility in all groups of contributing muscles before and during scrummaging to evaluate this.

The moderate to good relationship between the change in pelvic height and change in force during the start-sustained phase indicates how the lowering of the pelvis increased the individual forces. The change in the pelvic height percentage was negatively correlated to the change in forces during the engagement-sustained and peak-sustained phases. The position of the whole body centre of mass (CoM) is located near this area (McKinon et al., 2004) and the movement of the CoM may be responsible for the change in the scrummaging force for this duration. Sayers (2007) reported an increase in the linear velocity of the CoM (specifically the forward movement) with increasing the number of active scrummaging participants. This

finding highlights the possible importance of the positioning of the whole body CoM in the development and sustainment of scrummaging forces.

Unlike the data for correlations between body positions (joint angles) and force generation, where optimal scrummaging angles were not evident, the changes in the joint angles were representative of changes in force generation. These relationships do affirm the roles of individual bony levers in force generation during scrummaging. The change in forces during the engagement-peak phase was positively correlated to the change in right hip angle and negatively correlated to the change in right knee angle. Similarly during the engagement-sustained phase the changes in the individual forces were positively correlated to the changes in left hip angle and right ankle angle. These kinematic variations over time may be related to changes in muscle activity. The quadricepses are responsible for the extension of the knees and peak muscle activity occurs between 80-90 degrees flexion (Schoenfeld, 2010). Sharp et al. (2014) reported that on engagement the muscle activity is larger in the back muscles than those in the thighs, however the quadriceps exhibited larger activity than the hamstrings. The muscle activity in the hamstrings remains low throughout individual scrummaging.

A larger extension of the hip was found to be related to larger forces during both the engagement-peak and engagement-sustained phases. The extension of the hip may result in larger activation of the lower back and quadriceps. Sharp et al. (2014) showed a large percentage of maximal voluntary contraction of these muscles during the phase corresponding with the engagement-peak phase in the current study. Although these relationships do not necessarily indicate a causal role between limb movement and force generation, they are consistent with the theoretically implicit roles of the limbs in the generation and maintenance of scrummaging force. In agreement with such a contention, Quarrie and Wilson (2000) reported a significant regression model that showed how heavier,

more powerful players that exhibited a larger hip angle produced larger individual scrummaging forces.

During the engagement-sustained phase there was a moderate to good relationship with the change in force magnitude and the change in ankle flexion. Flavell et al. (2013) reported larger differences in the knee and ankle extensions as a defining feature between attacking and defending scrums. The relationship between the ankle and the engagement-sustained phase may be as a result of the interaction between the playing surface and the foot (Milburn & Barry, 1998). The combined surface area of the feet and the depth to which the studs of the boots are planted may allow for a greater force to be developed. du Toit et al. (2004) inferred that the resultant scrum force is originally derived from the interaction between the foot and the ground. Looking at the squat, which has a similar closed chain motion to the scrum, increased knee torque, came at the expense of reduced ankle torque during the upward motion (Dionisio et al., 2008). Similarly by increasing the degree of ankle dorsiflexion the knee cannot achieve the same amount of flexion, compared to the plantarflexion position (Macrum et al., 2012). These two effects may result in the extension of the knee while increasing the plantarflexion of the ankle to ensure maximal transfer of force during scrummaging.

Individual performance applied to the team setting

The current study has only tested individual players from the tight five of the entire eight-man scrum. Previously, the individual force contributions have been shown to have a moderate relationship to the entire group force (Quarrie & Wilson, 2000). The contributions of the forces within the scrum are not equally distributed between players. The players in the front rows contribute more force than locks and loose forwards (du Toit et al., 2004) or display smaller variations in the direction of force generation (Green et al., 2016). Similarly it

has been shown that locks produce more forward force than the loose forwards (du Toit et al., 2004). The kinematics of the individual will undoubtedly be different between the different playing positions. Saletti et al. (2013) showed how the individual kinematics of the trunk are not the same for all individuals during team scrummaging. Additionally Sayers (2007) showed how differences in body kinematics at setup, peak hip and knee velocities, and time to peak velocity for the hips, knees and ankles were dependent on the number of individuals in the scrum. Furthermore, the assessment of an individual may not reflect the player's performance when in the team's scrum. In fact, an individual's performance may be impeded by the addition of other players in the team scrum (Milburn, 1993).

The results of the current study have identified the relationships between body kinematics and the individual scrummaging forces, where stance width, pelvic and shoulder height appear to be important in the generation of scrummaging forces. Although limb positioning appears not to be important in the generation of forces the changes in these angles correspond to changes in force generation. The latter finding may suggest that multiple limb positioning strategies (rather than a single idealised body position) might be important for successful scrummaging performance.

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References

Brown, J.C., Lambert, M.I., Verhagen, E., Readhead, C., van Mechelen, W. & Viljoen, W. (2013). The incidence of rugby related catastrophic injuries (including cardiac events) in South Africa from 2008 to 2011: a cohort study. *British Medical Journal Open* 3: e002475. doi:10.1136/ bmjopen-2012-002475.

Cazzola, D., Preatoni, E., Stokes, K., England, M.E. & Trewartha, G. (2014). A modified prebind engagement process reduces biomechanical loading on front row players during scrummaging: a cross-sectional study of 11 elite teams. *British Journal of Sports Medicine,*1-6. doi:10.1136/bjsports-2013-092904.

Dionisio, V.C., Almeida, G.L., Duarte, M. & Hirata, R.P. (2008) Kinematic, kinetic and EMG patterns during downward squatting. *Journal of Electromyography & Kinesiology*, 18, 134–143.

du Toit, D.E., Olivier, P.E. & Buys, F.J. (2005). Kinetics of full scrum and staggered scrum engagement in under-19 schoolboy rugby union players. *South African Journal for Research in Sport, Physical Education and Recreation,* 27: 15-28.

du Toit, D.E., Venter, D.J.L., Buys, F.J. & Olivier, P.E. (2004). Kinetics of rugby union scrummaging in under-19 schoolboy rugby forwards. *South African Journal for Research in Sport, Physical Education and Recreation,* 26: 33-50.

Duthie, G., Pyne, D. & Hooper, S. (2003). Applied Physiology and Game Analysis of Rugby Union. *Sports Medicine,* 33(13): 973-991.

Flavell, C., Sayers, M.G.L., Gordon, S.J. & Lee, J.B. (2013). Mechanisms for triceps surae injury in high performance front row rugby union players: A kinematic analysis of scrummaging drills. *Journal of Sports Science and Medicine,* 12: 159-164.

Fuller, C.W., Brooks, J.H.M., Cancea, R.J., Hall, J. & Kemp, S.P.T. (2007). Contact events in rugby union and their propensity to cause injury. *British Journal of Sports Medicine*, 41: 862-867.

Green, A., Kerr, S., Dafkin, C., & Mckinon, W. (2016). The calibration and application of an individual scrummaging ergometer. *Sports Engineering 19*(1), 59-69.

Hendricks, S., Lambert, M.I., Brown, J.C., Readhead, C. & Viljoen, W. (2014). An evidence-driven approach to scrum law modifications in amateur rugby played in South Africa. *British Journal of Sports Medicine,* 48: 1115-1119.

Macrum, E., Bell, D.R., Boling, M., Lewek, M. & Padua, D. (2012). Effect of limiting ankle-dorsiflexion range of motion on lower extremity kinematics and muscle-activation patterns during a squat. *Journal of Sport Rehabilitation*, 21, 144-150.

McKinon, W., Hartford, C., Di Zio, L., van Schalkwyk, J., Veliotes, D., Hofmeyr, A. & Rogers, G. (2004). The agreement between reaction-board measurements and kinematic estimation of adult male human whole body centre of mass location during running. *Physiology Measurement,* 25: 1339-1354.

Milburn, P.D. The kinetics of rugby union scrummaging. (1990). *Journal of Sports Sciences*, 8: 47-60.

Milburn, P.D. (1993). Biomechanics of Rugby Union Scrummaging: Technical and safety issues. *Sports Medicine*, 16(3): 168-179.

Milburn, P.D. & Barry, E.B. (1998). Shoe-surface interaction and the reduction of injury in rugby union. *Sports Medicine*, 25: 319-327.

Noakes, T.D. & du Plessis, M. (1996). Rugby without risks. (First Edition) Pretoria South Africa. J.L. van Schaik Publishers.

Portney, L. G., & Watkins, M.P. (2009). Foundations of Clinical Research: Applications to Practice (Third Edition ed.). London: Pearson Prentice Hall.

Preatoni, E., Stokes, K.A., England, M.E. & Trewartha, G. (2013). The influence of playing level on the biomechanical demands experienced by rugby union forwards during machine scrummaging. *Scandinavian Journal of Medicine and Science in Sports,* 23: e178-184.

Preatoni, E., Stokes, K.A., England, M.E. & Trewartha, G. (2014). Engagement techniques and playing level impact the biomechanical demands on rugby forwards during machine-based scrummaging. *British Journal of Sports Medicine,* 49(8): 520-528.

Quarrie, K.L. & Wilson, B.D. (2000). Force production in the rugby union scrum. *Journal of Sports Sciences,* 18: 237-246.

Roberts, S.P., Trewartha, G., England, M. & Stokes, K.A. (2014). Collapsed scrums and collision tackles: what is the injury risk? *British Journal of Sports Medicine,* 49(8): 536-540.

Rodano, R., & Pedotti, A. (1988). A quantitative analysis of thrust and motor coordination in a rugby scrum. In A. Lees & K. Davids (Eds) *Science and Football I*, 416-425. London: E & FN Spon.

Saletti, D., Chicoulaa, G., Raszoudowsky, M., Drevelle, X., Piscione, J., Retière, D. & Laporte, S. (2013). Kinematic and dynamic responses of the scrum. *Computer Methods in Biomechanics and Biomedical Engineering*, 16(1): 204-205.

Sayers, M. (2007). Kinematic analysis of high-performance rugby props during scrum training. In T. Reilly and F. Korkusuz (Eds) *Science and Football VI*, 46-51. New York: Routledge.

Schoenfeld, B.J. (2010) Squatting kinematics and kinetics and their application to exercise performance. *Journal of Strength and Conditioning Research*, 24(12): 3497–3506.

Sharp, T., Halaki, M., Greene, A. & Vanwanseele, B. (2014). An EMG assessment of front row rugby union scrummaging. *International Journal of Performance Analysis in Sport*, 14: 225-237.

Taylor, A.E., Kemp, S., Trewartha, G. & Stokes, K.A. (2014) Scrum injury risk in English professional rugby union. *British Journal of Sports Medicine*, 48: 1066–1068.

Trewartha, G., Preatoni, E., England, M.E. & Stokes, K.A. (2015). Injury and biomechanical perspectives on the rugby scrum: a review of the literature. *British Journal of Sports Medicine,* 49: 425–433.

World Rugby. Laws of the game Law 20.1. (2015) http://laws.worldrugby.org/?law=20 Accessed 20.10.15.

Wu, W.L., Chang, J.J., Wu, J.H. & Guo, L.Y. (2007). An investigation of rugby scrummaging posture and individual maximum pushing force. *Journal of Strength and Conditioning Research*, 21: 251–258.

Chapter 8:

Psychological and physiological fatigue does not correspond to decreased scrummaging performance over a simulated rugby match. Andrew Green, Samantha Kerr, Benita Olivier, Chloe Dafkin, Rebecca Meiring and Warrick McKinon. Manuscript submitted to the *Journal of Sports Sciences* for review.

Abstract

In Rugby Union, forwards are required to participate in the arduous activity of scrummaging throughout a game. The purpose of the study was to identify whether match induced fatigue modified individual scrummaging technique and reduced performance. Twelve forwards (body mass 106.2±13.3 kg; stature 179.5±8.4 cm) had individual scrum kinetics and kinematics assessed prior to and following a protocol that simulated a rugby match. The simulated rugby match protocol required participants to run at various velocities and perform rugby specific tasks. Rate of Perceived Exertion (RPE) was assessed using a 6-20 Borg scale and Visual Analogue Scale (VAS). Blood lactate, heart rate and RPE were measured prior to, mid-point and after the simulated game, while markers of muscle damage (blood creatine kinase (CK) and urea) were measured prior to and following the protocol. RPE (p<0.0001) and VAS (p<0.0001) showed significant increases between the pre- and post-simulation values. Of the physiological markers, heart rate (p<0.0001) and blood urea concentration (p=0.004) increased following the simulation. No significant differences were observed for blood CK (p=0.281), individual scrummaging forces (p=0.433) or in the kinematic variables following the protocol. This lack of difference may suggest that individual strategies for attaining peak force may compensate for fatigue.

Introduction

The game of rugby is a high impact sport where bouts of considerable anaerobic effort are interspersed with periods of high intensity sprints, active recovery and passive recovery (Roberts et al., 2008). The individual demands of playing rugby are related to the players' positions (Quarrie et al., 2013; Jones et al., 2015; Lindsay et al., 2015), with backs required to participant in dynamic aerobic events compared to the forwards' moderately static, high intensity activities. The scrum is a specific and major component to the game of rugby union. A scrum requires eight players (forwards) from opposing sides to compete in a physical push for possession of the ball. Although much of the dynamics of force production in a scrum as a whole, is yet to be revealed, the production of individual scrummaging force is thought to be related to anthropometrical (Quarrie and Wilson, 2000), physiological (Quarrie and Wilson, 2000; Sharp et al., 2014) as well as biomechanical factors (Wu et al., 2007). Attacking scrums are presumed to produce more forward force than defending scrums (Flavell et al., 2013), which may infer that a psychological influence may exist surrounding the production of force.

Within a competitive match, a player can cover a distance of more than 4000m at various velocities (Duffield et al., 2012; Quarrie et al., 2013; Jones et al., 2015). This physical effort requires players to have a high level of aerobic fitness and efficient physiological mechanisms to maintain a high level of performance in all the specialised aspects of the game. In the related code of rugby league, both physical and technical performance has been reported to decrease in the final stages of a match (Kempton et al., 2013). Additional markers of fatigue, psychological (Mashiko et al., 2004) and physiological (Takarada, 2003; Mashiko et al., 2004; Smart et al., 2008; McLellan, Lovell, & Gass, 2010; McLellan et al., 2011), have been shown to increase following competitive rugby games. The role of fatigue, and its

effects on performance of scrummaging, may be a major contributing factor to the overall success of a team.

The purpose of the study was therefore to identify whether simulated match induced fatigue can alter an individual's scrummaging technique (as determined by kinematics) and reduce performance (as determined by scrummaging force measurements). It was hypothesised firstly, that individual scrummaging forces would decline as a result of the match simulation, and secondly that individual scrummaging kinematics would change.

Methods

Participants

Twelve university-level playing forwards (body mass 106.2±13.3 kg, stature 179.5±8.4 cm) had individual scrum kinetics and kinematics measured prior to and following a simulated rugby match protocol. Study approval was given by the Human Research Ethics Committee of the University of the Witwatersrand (M131019) and written informed consent was obtained prior to the study.

Study design

The study was an intervention design, conducted at a hard floor indoor gymnasium during the pre-season (four weeks prior to the start of the inter-varsity tournament), with the squad training in 8 field sessions and 4 gym sessions per week. The intervention was performed between 14:00-16:00, following the mid-week rest day replacing one of the week's gym sessions. The average indoor temperature was 23°C.

Instrumentation and equipment

Individual scrummaging kinetics and kinematics

Individual scrummaging forces were collected using an individual scrummaging ergometer at 160Hz. The accuracy of the device is reported by Green et al., (2016). The vertical and horizontal centre of pressure positions of the peak force, and the scalar distance of the peak force from the centre of the scrum ergometer were calculated. All kinematics were collected simultaneously to the individual scrummaging kinetics using an 18 camera system recording at 100 Hz [Optitrack flex:V100r2 (Natural Point Inc., Corvallis, Oregon, USA)] using AMASS software (C-Motion Germantown, Maryland, USA). A measurement volume of approximately 12 m^3 was calibrated around the scrummaging ergometer, in the area of scrummaging using a conventional wand method, until sub-millimetre error was established. Custom written algorithms (see below) were used to analyse body positions as derived from raw marker location data in MatLab 7 (Mathworks, Natick, Massachusetts, USA).

Psychological measures of fatigue

The individuals' ratings of perceived exertion were collected using a 6-20 Borg scale (Borg, 1970) and a 100mm Visual Analogue Scale (VAS) using 'not exhausted (well rested)' as the lower anchor and 'most exhausted ever experienced' as the upper anchor. Data for both ratings of perceived exertion were collected prior to, at half time and following the simulated rugby match protocol.

Physiological measures of fatigue

Heart rate was measured electrocardiographically using a Powerlab 26T (ADI instruments, 26T, Australia) and calculated as the number of R-R intervals within one minute. Surface electrocardiograph electrodes were place on the wrists bilaterally, and grounded on the right calves. Blood samples were collected via a finger prick using a spring loaded lance (Soft-Clix pro, Roche Basel Switzerland). All samples were analysed immediately following their collection. Blood lactate was analysed using a portable blood lactate meter (Lactate Pro 2, Arkray, Kyoto, Japan). Blood creatine kinase (CK) and urea were analysed using a Reflotron (Roche, Roche Basel Switzerland). The Reflotron was calibrated using the manufacturer specified procedure. Body mass was measured using a standardised digital scale (Tanita BC-1000plus, Tanita Corporation of America Inc, USA). Height was measure using a custom standardised stadiometer.

Procedure

Participants undertook a guided warm-up that included active and passive stretching and self-determined submaximal sprints (40-60% maximum) as they would prior to a match. Additionally they went through one cycle of the simulated rugby match protocol to familiarise themselves with the procedures.

The simulated rugby match protocol was based on the Bath University Rugby Shuttle Test (BURST) developed by Roberts and colleagues (2010). This rugby match simulation requires players to run at various speeds, and perform tasks specific to an 80-minute rugby union game: rucks, mauls and scrums. The simulated rugby match protocol lasting a total of 80 minutes is divided into 16 cycles, each of which has five task units. The task units require the player to perform 20m forward walk at 20% maximal sprint; come to a complete stop and turn; 20m forward cruise at 60% maximal sprint; come to a complete stop and turn; 10m

forward jog at 40% maximal sprint; perform a rugby specific task either a ruck, maul or scrum; 10m backward jog at 40% maximal sprint. Minor alterations were made to the BURST in an attempt to safely increase the amounts of physical collisions between two simultaneously tested individuals. Rucks were performed using a tackle shield (Gilbert, Grays of Cambridge (Int) Ltd, East Sussex, United Kingdom) where the defender held the tackle shield while the attacking player completed the tackle and maintained a steady leg drive for five metres. Mauls were statically simulated and required the attacker to gain possession of the rugby ball, by wrestling it from the defender. The defender was required to retain ball position for up to seven seconds. Scrums were performed one-on-one with the defending player instructed to actively resist the attacking player, while the attacking player attempted to maximally push the defender backwards for five metres. Players would alternate between attacking and defending roles during each task unit. The participants had a half time break of 10 minutes following the eighth cycle, during which they were able to drink a maximum of 500ml of water.

Individual scrummaging kinetics and kinematics, psychological measures, heart rate and blood urea, lactate and CK concentrations were analysed before and within ten minutes after the match simulation protocol. Blood lactate, psychological measures of fatigue (VAS and Borg scale) and heart rate were additionally collected at half-time.

Data reduction

Scrummaging back flexion was calculated as the degree of flexion between the lower and middle back around thoracic vertebrae ten (Figure 8.1). The angles of the hips were calculated as the angle between the back vector (mid hip joint centre to mid scapulae) and the femur vector (hip joint centre to knee joint centre). Bilateral knee and ankle flexions were calculated as the angle of flexion between the vectors of the femur and the shank (knee joint

centre to ankle joint centre), and the angle of flexion between the vectors of the shank and the foot (ankle joint centre to toe), respectively. Angles of 180° indicated a straight back and full extension of the hip and knee, respectively.

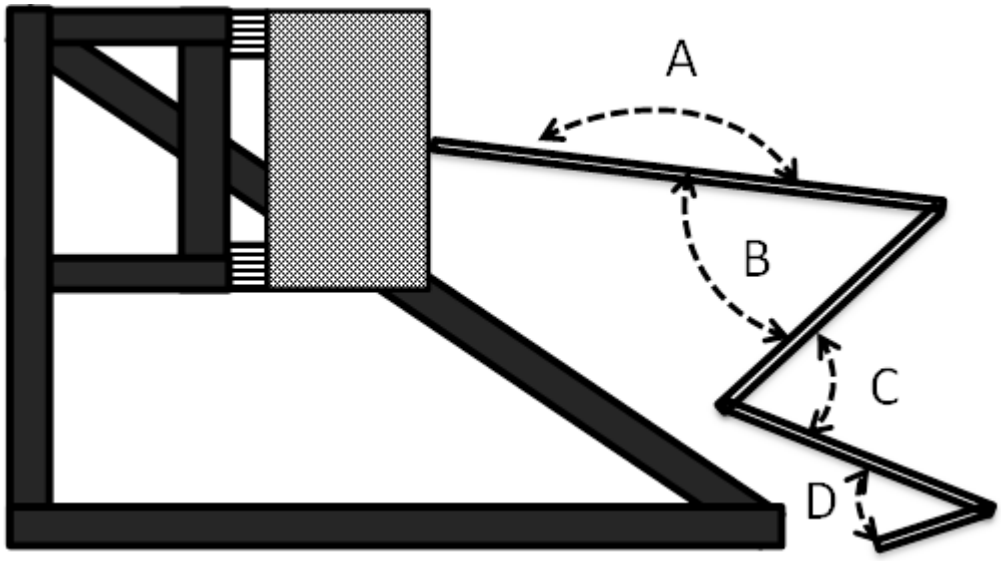


Figure 8.1: Kinematic definitions of variables in the starting position from the sagittal view. All variables are calculated bilaterally. A. Back flexion. B. bilateral hip extension. C. bilateral knee flexion. D. bilateral ankle flexion.

Statistical analysis

All data were tested for normality (Shapiro-Wilk test). All normally distributed variables are represented as mean ± standard deviations. The VAS scores and heart rates were analysed using a repeated measures one-way ANOVA. Body mass, blood CK, urea, and individual scrummaging kinetics and kinematics were assessed using paired t-tests. The distributions of blood lactate and Borg scale values are represented as median ± interquartile range and were assessed using a Friedman test. All statistical analyses were performed in GraphPad Prism 5

(GraphPad, San Diego, California, USA) using a significance level $p<0.05$. Effect sizes were determined using Cohen's d and interpreted using definitions established by Hopkins (2002): trivial $0<d<0.2$; small $0.2<d<0.6$; moderate $0.6<d<1.2$; large $1.2<d<2.0$; very large $2.0<d<4.0$.

Results

Psychological and physiological effect of fatigue

The rating of perceived exertion measured using the 6-20 Borg scale (Table 8.1) increased between the start and half-time (d=2.3) and between the start and end of the match simulation (d=3.6). No significant difference was observed in the rating of perceived exertion using the Borg scale between the half-time point and the end point (d=1.0). The second psychological marker for fatigue, the VAS, increased significantly between the start and half-time (d=0.98), the start and end (d=1.9), and half-time and end (d=0.7) of the match simulation. Heart rates were shown to significantly increase between the start and half-time (d=3.4) and start and end (d=4.0) of the match simulation, but not increase between the half-time and end points (d=0.3).

Table 8.1: The rating of perceived exertion, heart rate and blood lactate, creatine kinase and urea concentrations at three time points during a rugby match simulation protocol (n=12).

	Time point collection		
Fatigue measurements	Pre	Half time	Post
	Mean (±SD)	Mean (±SD)	Mean (±SD)
Borg scale rating (AU)[*ab]	6.5 (±2.8)	13.0 (±3.5)	16.5 (±4.8)
Visual Analogue Scale (mm)[abc]	30.6 (±25.9)	56.0 (±23.8)	71.4 (±20.7)
Heart rate (beats/min)[ab]	74.9 (±10.5)	110.9 (±21.6)	116.8 (±20.6)
	Mean±SD (CV)	Mean±SD (CV)	Mean±SD (CV)
Blood lactate (mmol/l)[*a]	1.80±1.60 (1.13)	3.45±3.55 (0.740)	2.90±3.25 (0.755)
Blood Creatine Kinase (U/l)	203.8±191.7 (0.941)	N/A	278.1±212.1 (0.763)
Blood Urea (mg/dl)[b]	34.6±11.5 (0.332)	N/A	46.5±12.9 (0.277)

[*]Borg scale rating and blood lactate concentration are represented as median ± interquartile range

AU Arbitrary Units

N/A Not Analysed at this time point

[a] significantly different between pre and half time (p<0.05)

[b] significantly different between pre and post (p<0.05)

[c] significantly different between half time and post(p<0.05)

Assessing the physiological fatigue markers (Table 8.1): blood lactate was significantly higher at half-time compared to the start (d=1.0), but no significant difference was reported between the start and end (d=0.7) or between the half-time point and end point (d=0.2) of the match simulation. There was no significant difference in CK immediately following the simulated rugby match protocol (d=0.4). A significant increase in blood urea was observed following the simulated rugby match protocol (d=1.0). Body mass was significantly reduced from 106.2±13.3 kg to 105.0±12.9 kg following the rugby match simulation protocol (p<0.001; d=0.1).

Effect of fatigue on scrummaging kinetics and kinematics

The force magnitudes, peak force centre of pressure positions and peak force position distance from centre are reported in Table 8.2. The paired t-tests showed that individual peak forces, positional distance from the centre of the ergometer, horizontal or vertical force positions were not significantly different following the simulated rugby match. Effect sizes of the kinetic measurements are considered to be trivial.

Table 8.2: Individual peak forces, centre of pressure scalar distance from centre, horizontal centre of pressure positions and vertical centre of pressure positions and individual scrummaging kinematics before and after a rugby match simulation protocol (n=12).

	Time point collection				
	Pre	Post			
	Mean (±SD)	Mean (±SD)	Difference	*p* value	Cohen's *d*
	Kinetic measurements				
Peak force (N)	1719.6 (±363.3)	1679.4 (±354.9)	-40.2	0.43	0.11
Peak Force distance from centre (m)	0.362 (±.078)	0.366 (±.073)	0.0037	0.86	0.05
Peak Force horizontal position (m)	0.012 (±.016)	0.016 (±.026)	0.0042	0.67	0
Peak Force vertical position (m)	-0.362 (±.078)	-0.365 (±.073)	-0.0032	0.88	-0.04
	Kinematic measures				
Back flexion (°)	169.9 (±6.3)	170.7 (±5.4)	0.8	0.91	-0.14
Right hip extension (°)	107.3 (±30.4)	120.7 (±24.4)	13.4	0.15	-0.49
Left hip extension (°)	98.5 (±35.1)	113.9 (±33.8)	15.36	0.25	-0.45
Right knee flexion (°)	54.9 (±11.3)	46.7 (±22.1)	-8.19	0.3	0.47
Left knee flexion (°)	57.2 (±20.9)	52.2 (±21.6)	-4.94	0.53	0.23
Right ankle flexion (°)	90.6 (±16.6)	87.2 (±17.1)	-3.38	0.62	0.2
Left ankle flexion (°)	87.2 (±19.1)	90.1 (±11.2)	2.9	0.51	-0.19

There were no significant differences in the lower limb and back kinematics following the simulated rugby match protocol (Table 8.2). Effect sizes following the simulated rugby match protocol are considered to be within the range from trivial to small for the lower limb and back kinematics.

Discussion

It was expected that individual scrummaging forces would decline as a result of the match simulation; however, no significant differences were observed in the scrum kinetic parameters. Secondly it was hypothesised that individual scrummaging technique (kinematics) would be negatively affected following the rugby match simulation protocol. Contrary to our expectations and despite the evident fatigue, no differences were observed in the kinematic variables following the match protocol.

Perceived fatigue

Psychological fatigue was recorded in the current study using two different subjectively reported scales, both of which showed a marked increase (very large effect size) in perceived effort. Mashiko et al. (2004) showed how a competitive rugby game can induce physical and mental fatigue. The results of the present study agreed with the former and others (Roberts et al., 2010; Singh et al., 2010; Mullen et al., 2015) with increased rating of perceived exertion increasing as the duration of match simulations progresses. Physiologically there was an increased heart rate between the start and half time and start and the end of the simulation. This corresponds with observations made in the development of the BURST (Roberts et al., 2010) and in a team game circuit (Singh et al., 2010). While heart rates were shown to increase during the protocol, the heart rates in the current study were lower than those noted

by Roberts et al. (2010) 158 beats per minute. These lower values for the heart rates may result from the electrocardiography used in this study (as compared to heart rate monitors, which may include some degree of electromyographic artefact). The heart rates reported by the Roberts et al. (2010) study was collected as the mean for the five-minute duration throughout the simulation, whereas the heart rate measured in the current study was only collected as single short-duration measurements with the participants seated: prior to, during the half-time break, and following the intervention. Further differences may be related to the fitness levels of the participants in the various studies.

In the current study blood lactate was significantly increased from before exertion to half-time, but not from half-time to post exertion or pre- to post exertion. Even though lactate significantly increased from before exertion to half-time the concentration never went above onset of blood lactate accumulation threshold of 4 mmol/L. It is likely that the intervention was more aerobic than anaerobic in nature and that the intensive static components were equally dispersed by active and passive recovery intervals. Roberts et al. (2010) reported higher peak blood lactate levels during the BURST (4.4-4.6 mmol/L) compared to the half-time blood lactate values in the current study. The discrepancies in the blood lactate are likely a result of the timing of blood collection. The BURST reported peak lactate value just after 20 minutes (Roberts et al., 2010) where the current study reported the half-time value and not as a peak value. If the peak lactate occurred before this time it would have been missed, giving the participants the opportunity to metabolise the lactate. Lactate (Takarada, 2003) and lactate dehydrogenase (Mashiko et al., 2004) have been reported to be increased following a competitive rugby game. It has been suggested that the intense static components of rugby, which forwards take part in, are responsible for the increased anaerobic fatigue markers (Deutsch et al., 1998; Austin, et al., 2011). Recent data from Morel and colleagues (2015) would dispute that the static components of rugby are solely responsible for the increased

blood lactate. They reported increases in blood lactate following scrum repetitions however the increase appears to be progressively lower in scrummaging compared to simulated mauling and sprinting (Morel et al., 2015). While the match simulation may emulate the tasks performed during a rugby match, it cannot simulate the intensity of a match. It is likely that the discrepancies are related to match intensity and the number of collisions resulting in muscle trauma and muscle breakdown. Significantly higher blood lactate concentrations have been reported in contact simulations compared to non-contact simulations (Mullen et al., 2015).

Physical contact in a rugby game is known to cause somatic blunt trauma and results in markers of muscle damage being released into the blood (Takarada, 2003; Mashiko et al., 2004; Smart et al., 2008). CK (an intramuscular enzyme and therefore a marker of muscle damage) is known to significantly increase in the plasma, following a rugby game (Takarada, 2003; Mashiko et al., 2004; Smart et al., 2008; McLellan et al., 2010; McLellan et al., 2011). The increase has been attributed to the physical impacts between players, specifically the tackle (Takarada, 2003) and scrum (Smart et al., 2008) and is thought to be related to the intensity of collisions (Mashiko et al., 2004; McLellan et al., 2010; McLellan et al., 2011). However in the current study CK did not increase following the simulated match protocol. The simulated game, while incorporating physical contact, was likely to include considerably lower impact collisions (less than those experienced during a game). This was to ensure player safety and was deemed safe to have live one-on-one scrummaging drills instead of a scrum sledge. However rucks and mauls had to be safely simulated using a cushioned tackle shield. These safety alterations undoubtedly affected the production of CK. Furthermore this lack of difference may be due to the physiological pathways by which CK presents in the blood. CK is released into the interstitial fluid resulting from muscle damage and is transported by the lymphatic system back into the blood for clearance (Smart et al., 2008).

Previous studies have shown how CK normally peaks hours after a rugby game (Takarada, 2003, McLellan et al., 2010, McLellan et al., 2011). The lack of an obvious increase in CK would tend to suggest that substantial muscle damage may not have been the cause of the psychological fatigue observed, and that metabolic fatigue (blood urea and blood lactate) may have been the cause of the psychological fatigue.

Another metabolite known to increase with a bout of fatiguing exercise is blood urea (Kyröläinen et al., 2008). Greater blood urea concentrations have been reported following competitive rugby (Mashiko et al., 2004) and soccer matches (Bangsbo, 1994; Andersson et al., 2008). In rugby players an increase in blood urea was reported in the forward players and was attributed to the contact and type of game play experienced by these players (Mashiko et al., 2004). Similarly the blood urea concentration was shown to significantly increase over the simulated rugby match in the present study. Although the mechanism by which the urea is present in the blood may be different to the muscle damage (as evidenced by the lack of an increase in CK in the current study) it is possible that such an increase is caused by different aspects of physical activity inherent to intermittent team sports (Bangsbo, 1994; Andersson et al., 2008).

Scrummaging kinetics and kinematics

The rugby match simulation protocol resulted in a reduction in body mass, similar to that seen in the BURST (1kg in both tests) (Roberts et al., 2010). The individuals' body masses are known to be related to the individual scrum force (Quarrie and Wilson, 2000; Sharp et al., 2014). Therefore it was expected that the scrummaging force would decrease. However the reduction in the body masses was considered to have a trivial effect size. Additionally, the greater scrummaging forces may be associated with factors linked to greater mass such as strength and therefore not be significantly affected by a minor reduction in the mass.

Furthermore there was no difference between the individual scrummaging forces prior or following the rugby match simulation protocol. However, the greater scrummaging forces may be associated with factors linked to greater mass such as strength and therefore not be significantly affected by a minor reduction in the mass. Nevertheless, the development of individual scrummaging force however is not solely reliant on the masses of the individual, but is related to technique (Wu et al., 2007).

The individuals managed to attain a similar peak force before and following the simulated rugby match (effect size: trivial) however this is contrasting to the results of Morel et al. (2015). Their study showed that an increase in the number of scrum repetitions reduced the individual scrummaging forces (Morel et al., 2015). Jougla and colleagues (2010) reported no differences between the peak forces following a rugby specific repeated sprint protocol. These two studies suggest that scrum performance is reduce by successive scrummaging attempts and not repeated sprints. It was expected that the peak scrummaging forces would be reduced following the match simulation since scrummaging is comparable with other measures of strength (Quarrie and Wilson, 2000), which have displayed a fatigue related decline in magnitude. Lower body peak power output, assessed via a counter movement jump, has been shown to be reduced following professional rugby union games (West et al., 2014) and a maximal sprint training session (Johnston et al., 2015). The difference between the known decline in jumping and sprinting performance and the lack of a decline in scrummaging performance is interesting and may relate to the different fatigue protocols or to the practised experience of scrummaging players. Their intrinsic ability to maintain a competitive scrummaging force may be developed over years of training, or the lack in difference might be due to the different impact nature of sprinting or jumping as compared to the high impact nature of scrummaging. The unchanging nature of scrummaging technique may however support the former explanation.

The resulting kinematics of the lower limbs showed that the individuals used a similar body position when applying peak force, regardless of their fatigued state. No significant difference was observed in either the peak individual forces or the body kinematics at peak force and their effect size ranged from trivial to small. Known correlates of individual scrummaging peak force are the extension of the hips, knees and flexion of the ankles (Wu et al., 2007). Sharp et al. (2014) reasoned that the lack of relationships between muscular activities and individual peak forces during engagement were due to a similar body position and engagement pattern used by the players. A similar effect may be present in the current study. The individual kinematics may not vary as a result of similar binding and individual scrummaging styles before and after the match simulation, and therefore the resistance to change of the scrummaging technique (kinematics) to fatigue appears to be a consistent finding.

Conclusions

While the participants were clearly in a state of fatigue, no differences were observed in the magnitude of their peak forces or in the body kinematics at peak force. The lack of difference in the peak force despite the fatigue may suggest that individual strategies for attaining peak force are resistant to fatigue but may be multifactorial and require a more in depth analysis.

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References

Andersson, H., Raastad T., Nilsson J., Paulsen G., Garthe I. & Kadi F. (2008). Neuromuscular Fatigue and Recovery in Elite Female Soccer: Effects of Active Recovery. *Medicine & Science in Sports & Exercise,* 40(2): 372-380.

Austin, D., Gabbett, T. & Jenkins, D. (2011). Repeated high-intensity exercise in professional rugby union. *Journal of Sports Sciences*, 29(10): 1105-1112.

Bangsbo, J. (1994). Energy demands in competitive soccer. *Journal of Sports Sciences,* 12: 5-12.

Borg, G. (1970). Perceived exertion as an indicator of somatic stress. *Scandinavian Journal of Rehabilitation Medicine, 2*(2): 92–98.

Deutsch, M.U., Maw, G. J., Jenkins, D., & Reaburn, P. (1998). Heart rate, blood lactate and kinematic data of elite colts (under-19) rugby union players during competition, *Journal of Sports Sciences*, *16*(6): 561-570.

Flavell, C., Sayers, M.G.L., Gordon, S.J. & Lee, J.B. (2013). Mechanisms for triceps surae injury in high performance front row rugby union players: A kinematic analysis of scrummaging drills. *Journal of Sports Science and Medicine,* 12(1): 159-164.

Green, A., Kerr, S., Dafkin, C., & Mckinon, W. (2016). The calibration and application of an individual scrummaging ergometer. *Sports Engineering 19*(1), 59-69.

Hopkins, W.G. (2002). A scale of magnitudes for effect statistics http://sportsci. org/resource/stats/effectmag. Accessed 20 November 2015.

Johnston, M., Cook, C.J., Crewther, B.T., Drake, D. & Kilduff, L.P. (2015). Neuromuscular, physiological and endocrine responses to a maximal speed training session in elite games players. *European Journal of Sport Science,* 15(6): 550-565.

Jones, M.R., West, D.J., Crewther, B.T., Cook, C.J. & Kilduff, L.P. (2015). Quantifying positional and temporal movement patterns in professional rugby union using global positioning system. *European Journal of Sport Science,* 15(6): 488-496.

Jougla, A., Micallef, J.P., & Mottet, D. (2010). Effects of active vs. passive recovery on repeated rugby-specific exercises. *Journal of Science and Medicine in Sport*, 13(3): 350–355.

Kempton, T., Sirotic, A. C., Cameron, M. & Coutts, A. J. (2013). Match-related fatigue reduces physical and technical performance during elite rugby league match-play: a case study. *Journal of Sports Sciences*, 31(16): 1770-1780.

Kyröläinen, H.,·Karinkanta, J.,·Santtila, M., Koski, H., Mäntysaari, M. & Pullinen, T. (2008). Hormonal responses during a prolonged military field exercise with variable exercise intensity. *European Journal of Applied Physiology*, 102(5): 539-546.

Lindsay, A., Draper, N., Lewis, J., Gieseg, S.P. & Gill, N. (2015). Positional demands of professional rugby. *European Journal of Sport Science*, 15(6): 480-487.

Mashiko, T., Umeda, T., Nakaji, S. & Sugawara, K. (2004). Position related analysis of the appearance of and relationship between post-match physical and mental fatigue in university rugby football players. *British Journal of Sports Medicine,* 38(5): 617-621.

McLellan, C.P., Lovell, D.I. & Gass, G.C. (2010). Creatine kinase and endocrine responses of elite players pre, during, and post rugby league match play. *Journal of Strength and Conditioning Research,* 24(11): 2908–2919.

McLellan, C.P., Lovell, D.I. & Gass, G.C. (2011). Biochemical and endocrine responses to impact and collision during elite rugby league *Journal of Strength and Conditioning Research*, 25(6): 1553-1562.

Morel, B., Rouffet, D., Bishop, D., Rota, S. & Hautier, C. (2015). Fatigue induced by repeated maximal efforts is specific to the rugby task performed. *International Journal of Sports Science & Coaching*, 10(1): 11-20.

Mullen, T., Highton, J. & Twist, C. (2015). The internal and external responses to a forward-specific rugby league simulation protocol performed with and without physical contact. *International Journal of Sports Performance and Physiology*, 10(6): 746- 753.

Quarrie, K.L., Hopkins, W.G., Anthony, M.J. & Gill, N.D. (2013). Positional demands of international rugby union: Evaluation of player actions and movements. *Journal of Science and Medicine in Sport*, 16(4): 353-359.

Quarrie, K.L. & Wilson, B.D. (2000). Force production in the rugby union scrum. *Journal of Sports Sciences*, 18(4): 237-246.

Roberts, S.P., Trewartha, G., Higgitt, R.J., El-Abd, J. & Stokes, K.A. (2008). The physical demands of elite English rugby union. *Journal of Sports Sciences*, 26(8): 825-833

Roberts, S.P., Stokes, K.A., Weston, L. & Trewartha, G. (2010). The Bath University Rugby Shuttle Test (BURST): A Pilot Study. *International Journal of Sports Physiology and Performance*, 5(1): 64-74.

Sharp, T., Halaki, M., Greene, A. & Vanwanseele, B. (2014). An EMG assessment of front row rugby union scrummaging. *International Journal of Performance Analysis in Sport*, 14: 225-237.

Singh, T.K.R., Guelfi, K.J., Landers, G., Dawson, B. & Bishop, D. (2010). Reliability of a contact and non-contact simulated team game circuit. *Journal of Sports Science and Medicine,* 9(4): 638-642.

Smart, D.J., Gill, N.D., Beaven, C.M., Cook, C.J. & Blazevich, A.J. (2008). The relationship between changes in interstitial creatine kinase and game-related impacts in rugby union. *British Journal of Sports Medicine*, 42(3), 198-201.

Takarada, Y. (2003). Evaluation of muscle damage after a rugby match with special reference to tackle plays. *British Journal of Sports Medicine*, 37(5): 416–419.

West, D.J., Finn, C.V., Cunningham, D.J., Shearer, D.A., Jones, M.R., Harrington, B.J., Crewther, B.T., Cook, C.J. & Kilduff, L.P. (2014). Neuromuscular function, hormonal, and mood responses to a professional rugby union match. *Journal of Strength and Conditioning Research,* 28*(*1): 194–200.

Wu, W.L., Chang, J.J., Wu, J.H. & Guo, L.Y. (2007). An investigation of rugby scrummaging posture and individual maximum pushing force. *Journal of Strength and Conditioning Research,* 21: 251–258.

Chapter 9:

Discussion

The current thesis was composed of seven original studies designed to evaluate the technical skill of individuals performing tasks specific to rugby. In this Chapter the results of the preceding Chapters (2-8) will be discussed with reference to the current literature and following from the evaluation of the literature in Chapter 1. Note that the discussions of the data pertaining to the individual studies of the specific performance tasks have already been considered and can be found within the defined discussion sections. In the sections that follow the major study findings are consolidated and examined, firstly focussing on ball passing in relation to the current knowledge of rugby passing performance. This is followed by a discussion of place kicking performance and the technical comparison of the place and drop kicks. Thereafter the implications of individual scrummaging performance will be analysed, followed by a discussion on the effects of fatigue on scrummaging performance. Following which an evaluation of the current studies in relation to a bigger picture of rugby performance is presented. Finally, this Chapter includes the proposition of future research ideas and the conclusion of the thesis.

The majority of the data from these studies reflect the ability of individual players to perform specified tasks, which in theory may or may not be related to rugby performance since the true reflection of performance in rugby is the rugby score (which will depend on the performance of both teams as well as each individual player). As discussed in Chapter 1 the evaluation of an individual rugby player's performance is a difficult measure to obtain therefore tasks need to be identified, which can be substantiated to reflect performance. The following three variables were the main measures of performance relevant to this thesis: passing accuracy, kicking distance and accuracy and scrummaging force. The stated rationale for the selection of these variables as indicators of performed is that: i) effectively passing a rugby ball to another player is a key component of game play; ii) the ability of a kicker who is more accurate is more likely to score points in a rugby game; and iii) that scrummaging

success is dependent on one team's ability to generate more forward momentum (through compressive force) than their opposition. In an attempt to determine and quantify the movement variables that predict performance, the tasks of running and ground passing, place and drop kicking and that of scrummaging were assessed in club level rugby players and in the field environment equivalent to the environment of actual rugby game play. In order to fully assess such variables related to scrummaging is was necessary to design and construct a scrummaging ergometer for the quantification of scrummaging forces and the effects of fatigue on scrummaging was also assessed. In the discourse that follows, the results of these studies are discussed with reference to the relevant literature and in the context of the rationale and objectives for this thesis.

9.1 Passing

The first two studies of this thesis investigated the self-selected technical strategies used by rugby players to accurately perform running and ground passes. Prior to testing, data to define the limits of a catchable pass was obtained from a group of rugby players from a variety of playing positions. These limits resulted in the construction of an accuracy target frame for use in the two subsequent studies.

The factors that have previously been identified as those that contributed to increased passing accuracy were hand dominance (Pavely et al., 2009; Sayers and Ballon, 2011; Worsfold and Page, 2014) and the role of different kinematic strategies (Worsfold and Page, 2014). Before a discussion of the determinants of passing accuracy can be made, consideration of the accuracy (and its measurement), is required. There have been various endeavours to measure passing accuracy (tabulated in Table 1.1, in Chapter 1) ranging in the design and application of the passing targets that have been used. The majority of these targets were designed to

assess the effects of an intervention on passing accuracy and not to determine the contributors to passing accuracy thus their design is occasionally limited (Stuart et al., 2005; Hooper et al., 2008; Assi and Bottoms, 2014). Arguably the most representative target was that designed by Worsfold and Page (2014), determined as the difference between the average rugby players' heights and the heights of their iliac crests. Worsfold and Page (2014) reported that the width of the target was based on the Greenwood's (1997) suggestion that a pass should be aimed 3 feet (0.91m) ahead of the receiver. This target at best represents the passive catchability of the player. However the ability to catch the ball should be represented in the dimensions of the target. The dimension should not be limited by assumptions of individuals catching abilities. Thus in the current thesis, passing accuracy was defined by the reported ideal limits of comfortable catching heights in rugby players. This approach to quantifying pass accuracy, to the author's knowledge, has never been attempted before. The participants were asked to define what they consider to be a catchable pass (maximum and minimum heights) when advancing during a game. This method may be an improvement from the previous models however it is not flawless. The limits of catchability were defined and influenced by the sample of individuals. The sample selected to define the passing limits were randomly selected from a larger sample population, but at the same club and playing level to those that were kinematically investigated. One could assume that the limits of catchability may be larger in more proficient players. The accuracy limits used in this thesis did however allow for a more relevant assessment of the passing outcome (perhaps tailored to limits relevant to the current players). The catching limits of the players must lie on a continuum and are restricted by their anthropometry (height and arm length). The selected sample used to define the limits of catchability may therefore be skewed and not fully representative of the entire populations abilities or preferences. However the selected sample may all have similar restrictions regarding the degree of catchability, as they were all selected from the same

playing club. The limits of catching ability while running in elite players remains unknown. Only speculation regarding the limits can be made. Two possibilities exist: either the limits would be greater, indicating that elite player are able to catch passes from a greater range of vertical limits. Conversely, the limits would be smaller. In the second case, having smaller limits, it may be that elite players are more aware of their catching limits.

The major finding of the first study was that no difference in passing accuracy was evident between the running pass strategies. The four strategies were based on the stepping sequence (STEP) of the players while running (in-step and out-of-step) and their whole body centre of mass position (CoM) prior to passing (raising or lowering). The latter two of these were previously investigated by Worsfold and Page (2014) however their results proved to be different to those reported in study one in this thesis which found no difference in the passing accuracy between the centre of mass manipulation techniques. Worsfold and Page (2014) reported that passes that included the body drop phase (lower the centre of mass) were more accurate. There are several possible reasons for the disagreement between the differences in accuracy between the current results and those presented by Worsfold and Page (2014). The most prominent difference is the quantification of the pass accuracy. Worsfold and Page (2014) used a binomial rating of accurate or inaccurate, depending on whether the ball struck the target or missed the target. As previously mentioned the current study made use of digital recordings of the ball passing through the target frame, which allowed for a more precise quantification of pass accuracy. A second difference between the studies is the pass distance. Worsfold and Page (2014) tested the accuracy of the pass over 4, 8 and 12m compared to the current study which assessed the pass accuracy over 10m. Worsfold and Page (2014) showed a reduction in pass accuracy over increasing target distances.

Another facet of the running pass that may affect the accuracy is the velocity at which the ball carrier is running. It has been suggested that individuals may reduce their velocity prior

to performing a task, be it passing or kicking (Barr et al., 2015). Pavely et al. (2009) and Worsfold and Page (2014) required their participants to run at 70% of their maximal running velocity. This submaximal velocity was considered to be representative of match running velocities. One limitation of the current study is that neither running velocity nor ball velocity was quantified. The participants in the current study ran at self-selected velocities that were representative of match velocities. The self-selected running velocities may have been significantly lower than 70% of maximal running velocity. The reduced velocity may have allowed for more accurate passes to be made, as the time for the pass execution would have been larger when running at a slower velocity. The effects of running velocity, including the instantaneous velocity at the initiation of the pass execution, and passing performance requires investigation.

In the subsections that follow the implications of the data from the passing studies will be discussed in regards to their kinematics differences between passing: strategies; direction; and accuracy, in the context of existing research. Additionally discussion relevant to the ground pass, hand dominance and overall assessment of passing performance will be conducted, citing relatable studies.

Kinematic differences between strategies

The four different kinematic strategies used to execute the running pass resulted in observably different limb motions. The CoM manipulation strategy exhibited the majority of kinematic differences in the bilateral flexions of the knee and ankle joints. It would seem that the CoM lowering strategy occurred with the CoM at a position lower to the ground and a greater head rotation than the CoM raising strategy. The STEP manipulation strategy exhibited the majority of kinematic differences in the rotations of the shoulder and the pelvic

girdles. The greater head rotation may indicate that individuals were quicker to identify the target in the CoM lowering strategy compared to the raising. However I could not accurately determine whether their eyes were fixed on the target, only the assumption that the rotation of the head and the position of the eyes are related can be made. A study to assess whether a shorter duration to identify the target could improve passing accuracy warrants investigation. Alteration in the kinematics of passing may not be exclusive to the strategy selected by the player. Worsfold and Page (2014) data showed, although not statistically significant, that the CoM lowering technique was employed more often when passing with the non-dominant hand (comparable to the non-dominant side, in the context of this thesis).

Kinematic differences between pass directions

As discussed in Chapter 1, differences in coordinative patterns between maximal passes towards the preferred and non-preferred side have been found (Pavely et al., 2009). In the present studies, a larger head rotation and a greater lateral bend angle for passes to the non-dominant side direction was observed, regardless of the strategy (CoM or STEP). Independently the CoM exhibited a greater degree of stance knee flexion and the STEP, greater pelvic rotations for passes to the non-dominant side direction. These two kinematics variables were shown to be specific features of the CoM and STEP manipulations and may represent the interactions between the passing strategies and the preferred/non-preferred side. That is, individuals may selectively alter their kinematic strategies depending on the direction of the intended pass. The implications of altering passing strategies may be beneficial in the sense that the pass is accurately or effectively executed, but as a result of the body kinematics, put the individual at risk of injury. The change in passing strategy could result in the passing player being in a position that predisposes them to a tackle-related injury. Further

investigations into the in-match passing strategies, along with clearer definitions of tackle related injuries occurring as a result of passing technique are required.

Differences in body kinematics and pass accuracy

Irrespective of the passing strategy used to execute the pass, no significant differences in the degree of body kinematics were noted when performing an accurate pass. However, lateral bend was the one common variable to all passing strategies that was implicated in more accurate passes. Lateral bend angle was defined as the abduction of the sagittal torso plane relative to the sagittal pelvic plane. Thus, the lean of the torso towards the target may allow for the effective delivery of the ball via the correct sequencing of the arms. Interestingly no differences in the arm kinematics between or within the different strategies were observed. This lack of difference would suggest that it is the contributions of the arms during the passing sequence that may be the discriminatory feature between accurate and inaccurate passes. With no previous or comparable data, this hypothesis is speculative and further investigation is required. It must be stressed that the strategies identified in these two studies occurred at the discretion of the participants, as they freely choose the sequence that they felt would result in the most accurate passes. Indeed the passes were accurate regardless of the utilised strategy.

The ground pass

The ground pass is executed from a relatively static position towards a structured group of players, which presents a greater target however still requires a refined degree of accuracy. The results from the second study (Chapter 3) revealed that two strategies are present in

players when performing the ground pass. These strategies were identified on the orientation of their pelvic girdle (and torso), which were either orientated with the leading shoulder directed towards the target (side-on) or the chest directed to the target (front-on). The data suggests that the side-on passing orientation is significantly more accurate than the front-on orientation. Consequently it was shown that different kinematic relationships were present between the two body orientations. The side-on orientation exhibited relationships between: the stance side elbow and wrist flexions; pass side wrist flexion and neck flexion; with passing accuracy. The front-on orientation exhibited relationships with: rotation of the head; pass side elbow flexion; and the degree of separation between the torso and pelvis with passing accuracy.

To date, one other study has investigated the ground pass, assessing the kinematic predictors and the effects of the preferred side of ground pass (Sayers and Ballon, 2011). There were methodological differences between the studies in this thesis and Sayers and Ballon (2011), whose investigation used a simple five-point scale to assess the passing accuracy and did not report the dimensions of the accuracy target. However Sayers and Ballon (2011) did identify different correlations in the preferred and non-preferred side passes. The non-preferred side pass velocity was related to the maximum velocity of the: internal rotation of the lead shoulder; adduction trail shoulder and trail arm elbow flexion. A common relationship regardless of the pass direction was maximum shoulder flexion of the lead arm (Sayers and Ballon, 2011). Surprisingly no significant relationships were reported between the body kinematics and pass accuracy. This may be a result of the rudimentary scores assigned to the pass accuracy. Additionally the lack of accuracy relationships may be attributed to the passing strategies used by the participants. Arguably the biggest difference between the studies was that no information regarding the participants' approaches to pass was reported (Sayers and Ballon, 2011). Another feature different from the Sayers and Ballon (2011) study

is that the current study did not assess the possible differences in preferred and non-preferred side passing accuracy. In both the current study and that of Sayers and Ballon (2011) a larger sample would have been beneficial to assess whether the ground pass is a positional specific task. Predictably the scrum-half is likely to be the most proficient at this task, as they perform the majority of these passes during a game. However the capability of other players to execute this pass and the degree of their accuracies necessitates further investigation.

Hand dominance

The issue of hand dominance raises an interesting point, especially in light that the pass in rugby is considered a dual handed task. The dual-handed nature of the pass may be argued to be incorrect. A better descriptor may be that there are active and passive hands involved in the pass. That is the right hand in a pass towards the right is the passive hand, while the left is the active hand, imparting velocity and spin onto the ball. Pavely and colleagues (2009) reported how passes made using the dominant hand travelled significantly further compared to the non-dominant hand. Furthermore more passes were noted to travel forward when executed with the non-dominant hand. Sayers and Ballon (2011) reported reduced ball velocity when assessing the hand dominance in the ground pass. No difference in the accuracy between dominant and non-dominant hand usage was observed in the running or ground passes in the first or second study in this thesis. The likely cause of this result is the usage of different strategies to perform the pass with the non-dominant hand. Worsfold and Page (2014) showed how the use of the centre of mass lowering technique was more prevalent with passes of increasing distance. This change in strategy may be beneficial in the sense that the pass can be accurately performed, however Worsfold and Page (2014) continued to show that the COM lowering technique took a significantly longer duration to

complete. The duration of the pass is essential to the performance of the pass as the player may not have had sufficient time to complete the pass before being tackled or before the space for attacking is occupied.

Overall assessment of passing performance

Passing in the context of a game requires more in depth analysis. Currently the use of notational analysis quantifies the amount of successful/unsuccessful passes and gives little information about the outcome. A pass is currently noted as successful if it is caught by the receiving player however no information is reported regarding the nature of the catch. If the receiving player has to alter their body positioning (reach up or down) for the ball, which could reduce their running velocity, then the pass, while successful, is not effective. An effective pass should be considered as one that is accurate enough that the receiving player's velocity is not impeded. Assessing the various strategies used to perform the pass, the importance of the ball delivery and not necessarily the strategy to perform the pass should be stressed. That is unless the ball carrier wants to potentially eliminate a player from the opposition, which would require the use of a draw-and-pass strategy.

Future research could assess the prevalence of different passing strategies and their outcomes within live games. Their results may impact the style of play and training regimes of player and teams. Notational analysis may allow for datasets regarding playing positions and passing strategies within live games. It may be that different playing positions utilised different passing strategies to varying levels of success.

9.2 Kicking

While the ability of a team to retain ball possession in a rugby game is vital to their success, the defensive gameplay of the opposition may demand territorial plays (kicks) for the attacking team to advance. There are numerous kicking types in rugby used for different purposes (see section 1.3.2.2). Some methods of kicking are used to gain field territory and others are used to gain points. The performance of the kick is heavily reliant on the ability of an individual, although kicking for a gain in field position may be more reliant on combined team performance. In the sections below I will discuss the performance of the place kick, distance and accuracy, and assess in greater depth the technical attributes of the drop kick. The results will be discussed in context of other football codes, including rugby league, soccer and American football.

Kick distance

As reported in chapter 1, the points accrued from kicking can account for nearly half that of a team's total (Quarrie and Hopkins, 2015) indicating that it is an essential aspect of the game. Therefore the third and fourth studies of this thesis were focussed on the individual performance of the point scoring kicks within rugby, namely the place-kick and the drop-kick. The primary hypothesis of the third study was that the major rotational components of the kinetic chain (the shoulder and pelvic girdles) would be related to the distance of the place kick. Indeed, significant relationships were shown between the shoulder and pelvic girdles and the place kick distance.

The relationship with torso rotation and kick distance confers with previous data on the soccer instep (Naito et al., 2010 Fullenkamp et al., 2015) and out-of-hand rugby kicks (Sinclair et al., 2013). The action of the torso rotation may also assist with the development

of the kick velocity (Naito et al., 2010; Sinclair et al., 2013; Fullenkamp et al., 2015). It must be noted that while the ball velocity was not measured in the current study, the kick distance was used as the performance outcome of the kick.

Previous studies have identified the importance of pelvic rotations and kick performance (Kallis & Katis, 2007; Sinclair et al., 2014b; Zhang et al., 2012). Similarly the increased rotation of the pelvic girdle with an increased kick distance was shown in the current study. The interaction between the torso and pelvis was expected to influence the kicking performance. Surprising findings were the lack of relationships between the lateral bend (sagittal plane separation of the torso and pelvis) and kick distance; and the degree of back flexion and kick distance. Additionally the difference between the torso and pelvic girdle along the vertical axis (X-Factor) was shown not to influence the kick distance. The lack of relationships may be a result of the refined kicking abilities of the participants within the current study. Shan and Westerhoff (2005) reported the use of a tension arc (described in section 1.5.3.2) in the attainment of greater kick distances. The tension arc model was used to distinguish between skilled and unskilled kickers, showing that skilled kickers utilized the tension arc to a greater extent.

Kick accuracy

While the success of a kick in rugby is partially dependent on the distance covered by the ball (Nel, 2013), the kick also requires a degree of accuracy to bisect the uprights. The measurement of the kick accuracy was determined as the degree of deviation of the landing position of the ball from a central line. The place kick accuracy was shown to be negatively correlated to shoulder girdle rotations and a lower degree of separation between the torso and pelvis. The degree of separation between the torso and pelvis, X-Factor, is a widely used

variable in golf research (Chu et al., 2010). The X-Factor in context of kicking may show an additional segment in the kinetic sequence. The extent of the rotation may be implicated in the generation of rotational momentum developed in the upper-body segment. While no relationship between X-Factor and kick distance was noted a correlation between X-Factor and kicking accuracy was observed. The negative relationship may show that a refined sequence of segmental control between the torso and pelvic girdle is required for more accurate kicks. This however is highly speculative and warrants further investigation. Furthermore this variable, X-Factor, requires validation within the context of kicking performance.

The participants were kicking from a distance of 50m which may have been on the limit of their maximal kicking abilities. This was chosen as it represents an estimate of the limit to most players place kicking distances (that is the distance that they would elect to attempt a penalty goal). Other researchers (Padulo et al., 2013) selected a distance of 40m from the posts, which is more achievable. However the degree of accuracy was not altered in the current series of studies nor was it in the Padulo et al. (2013) study. Note that a change in angle of kicking towards the posts (from different positions on the field) may increase the distance and the accuracy of the kick needed for successful conversion. Kinematic strategies may be different depending on the degree of kick difficulty. Further studies are required to evaluate potentially different kinematic strategies that related to kick accuracy of varying difficulties.

The drop kick

The 2016 experimental laws proposed by World Rugby have emphasised the importance of the drop kick. Under the experimental laws the drop kick will be an option for the defending

side once the ball has proceeded over the in-goal area (World Rugby Law Trials). Therefore maximising the distance of the drop kick will give the defending team an advantage in terms of field territory gain. Similarly a team may choose to kick the ball as far as possible when restarting the game in an attempt to optimise their field position.

The fourth study (Chapter 5) compared the kicking sequences of the place kick and the drop kick, specifically assessing the torso rotation, non-kicking side arm and stance and kicking knee kinematics. It was hypothesised that the two kicking sequences would be kinematically different based on the technical needs of the individual kicking types. It was expected that torso rotation, being a predictor of various different kicking types (Naito et al., 2010; Sinclair et al., 2013; Fullenkamp et al., 2015) would be greater in the place kick than the drop kick. However, only minor differences were observed in the preparatory phases between the place and drop kicks. The velocities of the torso rotations were significantly higher in the place kick at 30, 40 and 60% of the cycles. The greater rotational velocities in the drop kicks may be a result of the reduced degree of the torso rotation in the early stages of the kicking sequence. The torso in the drop kick may have to 'catch-up' to the familiar pattern of drop kicking by increasing its velocity during this phase. It was expected that the degree of torso rotation would be reduced in the drop kick as the upper body is required to drop the ball onto the ground. By limiting the torso rotation during this time the players may ensure an effective ball descent and rebound. Moreover the action of dropping the ball endorsed a reduction in the stance arm abduction. Remarkably no differences were found in the degree or velocity of abduction in the stance-side kicking arm between the two kicks. It was anticipated that the stance-side kicking abduction velocity would be significantly increased in the drop kick. The drop kick requires the placement of the ball from the hands towards the ground. While this usually occurs with the ipsilateral hand (Pavely et al., 2010) the contralateral hand does assist in the process. The differences may, if extrapolated backwards, be greater prior to the

commencement of the kicking cycle (that is the toe-off phase of the kicking foot-described by Nunome et al., 2006 and Charnock et al., 2009).

The most noteworthy finding in study four was the similarity in the velocities of the kicking knees such that no differences were found at any time point during the kicking sequences between the two kicking types. There was however a discernible difference between the kicking distances. Knee extension velocity is perhaps the best predictive parameter of ball velocity and kick distance (Zhang et al., 2012; Sinclair et al., 2014a; Sinclair et al., 2014b). The lack of difference between the kicking velocities may be attributed to the frequency of the kinematic system. The capture rate of 100Hz is not ideal for kicking where the extension velocity of the knee can be in excess of $2000°.s^{-1}$ (Nunome et al., 2006).

The approach of this study was based on the known determinants of kicking performance during the kicking sequence. It is possible that differences are exhibited between the kicking types as the dynamic action of the drop kick may have independent determinants from the place kick. Similarly the differences may occur outside of the observable sequence. The kicking sequence is largely based on the soccer in-step kicking action and measured from the toe-off of the kicking foot to the point of ball contact (Nunome et al., 2006; Charnock et al., 2009). However within the sequence of the drop kick, the ball is released prior to the toe-off artefact. Therefore the rugby drop kick may require its own sequence defined by its own mechanics. A suggested approach would include the following artefacts: stance-side hand removed from ball; kicking toe-off; ball released; stance foot planted; ball-ground contact; ball-foot contact. Compared to the current in-step soccer kicking sequence, the suggested approach would allow for the assessment of the upper-body movements that occur prior to the toe-off phase, and give additional artefacts that may prove to be valuable in the determination of differences between the two kicking types.

Additional differences may be observed in the ball-foot interactions and the ball-flight trajectories as the intended outcomes of the kicks may be inherently different. The interaction between the foot and the ball, specifically the position of the foot strike on the ball, will affect the launch angle, spin and distance (Asai, 2002; Pfeifer 2015). The lack of kinematic differences between the place- and drop-kick may be apparent, but the differences may be exhibited in the interactions of the foot with the ball. The outcome of the drop kick is more complex than just distance. A restart may be intentionally reduced distance wise, but the resulting kick trajectory may be high. A high restart is preferred by most teams as it gives the chasing players an opportunity to make up the ground and contest for the ball. To this end further studies should investigate the technical parameters related to the various drop-kicking outcomes. An approach similar to Pfeifer (2015) may be useful for both evaluating the pass and kicking outcomes. Pfeifer (2015) used 3D imaging to recreate the ball trajectory in American football placekicks. It was shown that the ball flight could be accurately recreated using a custom algorithm. The position of the ball relative to the posts could be quantified along with the ball flight allowing for the analysis of the spin that could cause the ball to shape in towards/away from the posts. Pfeifer (2015) focussed on American football, where all place kicks are taken directly in front of posts however the application of this technique to rugby where the field position could dictate the kicking shape would greatly contribute to the understanding of rugby kicking techniques and warrants further investigation.

The focus of the previous four studies has been on tasks that are largely dependent on individual performance. While the scrummaging performance of a team is dependent on interpersonal coordination, the individual contributions of single players can be assessed and related to the performance of an entire scrum and ultimately, a team. However, the total compression force of the team scrum is known to be less than the sum of the individual compression forces (Quarrie & Wilson, 2000; du Toit et al., 2005). Therefore, a successful

team scrum requires the coordinated efforts of individuals to produce a maximal compressive force.

9.3 Scrummaging

The fifth, sixth and seventh studies all investigated the individual performances of scrummaging. The first of these was the design, calibration and implementation of a custom-made individual scrum ergometer. The device was capable of accurately measuring the magnitude of the individual scrummaging forces and the position of the centre of pressure. Application of the device displayed playing position differences in the position of the applied force, but not the magnitude of the force. The sixth study evaluated the body kinematics of individual scrummaging performance. While no static parameters were related to scrummaging force, lower body heights and wider bases of support were associated with larger scrummaging force magnitudes. The final study assessed the effects of fatigue, derived from a simulated match, on scrummaging kinetics and kinematics. While the fatigue development was evident during the match simulation, no differences in the body kinematics or scrummaging kinetics were observed following the match simulation.

The purpose of the fifth study of this thesis was to contribute to the understanding of the dynamics of scrummaging. Consequently, a scrummaging ergometer was designed, constructed and assessed for accuracy, when measuring scrummaging forces and the direction of the force vector (as measured by the location of the centre of the applied pressure, CoP). Consequently an individual scrum ergometer with acceptable limits of agreement in terms of the force magnitude and CoP position measurements was developed. The scrummaging ergometer was used to assess the scrummaging kinetics of club level rugby forward players, with inherent errors of less than 4mm for the measurement of the location of scrummaging

CoP and negligible error of less than 17N (less than 1% of the actual measurements) in the measurement of force magnitude. Once validated, the new ergometer allowed for a second objective of study five to be fulfilled, where comparisons between the force magnitude and centre of pressure data between the different playing positions in the scrum were made.

The individual force magnitudes were not different between playing groups, which is in agreement with Quarrie and Wilson (2000). However it must be stressed that the forces measure in this thesis and those of Quarrie and Wilson (2000) were measured individually and the participants had no restrictions to their body postures. Players in the current series of studies were not constrained by the binding of other players, and were therefore able to select their own body postures. It has been reported that individual contributions within the scrum are not the same (Milburn, 1990; du Toit et al., 2004; du Toit et al., 2005) and the sum of the individual contributions may not reflect the force exerted by the team scrum (Quarrie and Wilson, 2000).

The magnitude of the individual scrummaging forces from the studies within this thesis will be discussed in context of current data in the sections below. Table 9.1 reports the various literature regarding individual scrummaging force magnitudes, with respect to the numerous factors (identified in chapter 1) that may affect the performance.

Inconsistency in the individual scrummaging magnitudes

From the data of recent studies there appears to be a trend towards increasing scrummaging forces over recent years. The increase in the maximal force can be associated with the increase in player size (Quarrie and Hopkins, 2007; Preatoni et al., 2013). Although, as noted

in chapter 1, mass alone is not responsible for the production of the exerted force and it is likely that technical advantages are also used (Preatoni et al., 2013).

The difference between the current series of studies and some of the previous research is related to differences in the engagement of the individuals on to the device. Previous studies have assessed various scrum engagement procedures (Preatoni et al., 2014; Cazzola et al., 2014) and others have highlighted the concern for potential injury risk surrounding the scrum engagement (Hendricks et al., 2014; Trewartha et al., 2015). This has lead the governing body of rugby union to actively reduce the engagement forces. The resulting new laws attempt to minimise the role of the initial contact (Preatoni et al., 2014; Trewartha et al., 2015), therefore the studies in this thesis have concentrated on a maximal sustained force instead of the accustomed peak force (usually observed upon scrum engagement (Preatoni et al., 2013; Preatoni et al., 2014; Sharp et al., 2014; Morel and Hautier, 2016). The players were all a predefined distance from the ergometer and additionally the manner in which they engaged the machine was remarkably reduced. This caused the accustomed engagement peak to be absent from the datasets. With the current laws of rugby aiming to minimise the 'engagement hit' from the scrum, the current series of studies therefore aimed to assess the development of peak force following the engagement peak. An additional reason for the absence of the engagement peak could be attributed to the frequency of the kinetic system. The frequency of the kinetic measurements will be discussed in the sections to follow.

Scrummaging forces and body mass

The relationship between scrummaging force magnitude and body mass was reported in chapter 6 (n=39) for peak force (r=0.510) and in chapter 7 (n=25) for engagement (r=0.641), peak (r=0.531), and sustained (r=0.438) forces. The relationship between individual scrummaging force and body mass has been previously reported in two other studies. Quarrie and Wilson (2000) reported correlation values (r=0.54; n=40) that were similar to those seen in the current study (Chapter 6). However, the study by Sharp and colleagues (2014) showed that these relationships were not always clear cut and depended on the level of play. There was a positive relationship for juniors (r=0.59; n=7), negative for seniors (r=-0.41; n=5) and no relationship was shown in the professional group (r=-0.01; n=5). Furthermore, there was also a lack of a correlation with the combined group of 17 individuals. A direct comparison with the average age and playing level of the participants in the Quarrie and Wilson (2000) study (average age: 23.2±3.1 years) can be made with the participants used in chapter 7 (average age: 22.5±2.9 years). In the same vein the junior group as reported by Sharp and colleagues (2014) is the best comparison for these datasets. Furthermore the playing levels of the participants were all equivalent between these studies, ranging from premier club (Quarrie and Wilson, 2000) to amateur age group players (Sharp et al., 2014). The playing level of the participants used in this thesis were either elite age-grouped players (under-19 and under-21) or actively playing for elite amateur clubs. Therefore the presented data agrees with the junior data presented by Sharp et al., (2014) thus providing further data for the relationship between force and mass at that playing level. However the higher playing levels (senior and elite) require further exploration with larger sample sizes than those included in the Sharp et al. (2014) study. Sharp and colleagues (2014) offer a hypothesis for the lack of relationship between mass and scrummaging force at the senior and professional playing levels. Their hypothesise is that junior players rely more on their mass for force generation

whereas senior and professional players rely on technique and strength (Sharp et al., 2014). This premise may be valid as Preatoni et al., (2013) reported that team scrummaging forces increase with increasing playing level irrespective of the increasing mass of the scrum. Thus showing the importance of other scrummaging attributes such as technique, coordination and muscular strength.

Playing levels of the individuals

Different playing levels have an effect on the forces produced during scrummaging (Preatoni et al., 2014) and on individual scrummaging performance (Sharp et al., 2014). The peak forces exerted by the professional group were substantially larger than the seniors and juniors within the Sharp et al., (2014) study. A similar effect can be seen with the individual force magnitudes and their playing levels from recent studies (Table 9.1). The playing levels range from juniors (Sharp et al., 2014) and age grouped players (Morel et al., 2015; Morel and Hautier, 2016) through to national (Wu et al., 2007) and professional players (Sharp et al., 2014). The majority of the individual scrummaging force data has been collected using sub-elite participants (those that are yet to represent their country). While it would be interesting to investigate this elite group, it is necessary to collect and assess the individual force magnitude along the spectrum of abilities. The individual scrummaging force can be seen to increase with the playing level of the individual, barring the Wu et al. (2007) study. The exclusion of the Wu et al. (2007) data is warranted as the mass of their participants are not comparable to other participants of lower playing levels. The definition of national players may not indicate that the participants were professional, or from a nation that regularly contested international test matches. Therefore I would suggest that comparisons made with the Wu et al. (2007) study be made with caution. There are however a few noteworthy

methodological and ecological differences between the studies that may affect the force magnitudes. Possible reasons for the dramatically larger values in scrummaging force magnitudes in the Sharp et al., (2014), Cazzola et al., (2015) and the studies present in this thesis (Chapters 6, 7 and 8) may be the higher measuring frequency of the ergometers and the level of friction between the ground and feet.

Measuring frequency of the scrummaging force

From Table 9.1 it is noted that the various studies have used different measurement frequencies ranging from 1-500Hz, resulting in differences in the resolution of the force data. A higher recording frequency is able to detect and record more dynamic events to a finer resolution than lower frequencies. The collision between the individual and the machine is a highly dynamic event, which results in larger compressive forces. If the capturing frequency is lower than the collision event, it may result in the reduction of the peak force or the inability to capture the peak force of the collision. The frequency of 160Hz used in the studies in this thesis may 'miss' the customary engagement force peak, or the reduced engagement peak as a result of the controlled engagement of the individuals. This discrepancy can affect the measurement of the peak force. The dynamic nature of the collision between the individual and the ergometer requires the use of a high enough measuring sample frequency to report the peak engagement force (normally the peak force). However the sustained force exerted during the contested scrum is the main performance indicator. The sustained force is less susceptible to dynamic change and can be assessed using lower frequencies. Overall the frequency of the force measurement should be determined by the variables of interest: higher frequencies for the evaluation of the impact; and lower frequencies for the assessment of the sustained force and its variation.

Table 9.1: Comparisons between individual force magnitudes, measurement frequency and maximal force, playing levels and ground compositions from recent publications and chapters 6, 7 and 8.

Study	Maximal force magnitude (N)	Body mass (kg)	Playing level	Measurement frequency (Hz)	Measurement of maximal force	Ground composition
Quarrie & Wilson (2000)	1370 ± 280	96.9 ± 9.8	Premier club	20	peak	Synthetic matting
Hot et al (2003)	1466 ± 244	96.9 ± 10.1	Club elite	NS	NS	NS
Wu et al., (2007)	1171 ± 277*	85.5 ± 9.61	National	1	peak	Indoor
Sharp et al., (2014)	4493 ± 151	112.1 ± 6.5	Professional	NS	peak	Synthetic matting
Sharp et al., (2014)	3091 ± 653	101.4 ± 9.3	Senior amateur	NS	peak	Synthetic matting
Sharp et al., (2014)	3362 ± 788	99.1 ± 6.0	Junior amateur	NS	peak	Synthetic matting
Cazzola et al., (2015)	2800 ± NS	102.36 ± 15	University 1st XV	500	peak	Indoor
Morel et al., (2015)	1609 ± NS	90.9 ± 9.8	Elite u-23	NS	average over 5 seconds	Synthetic track
Morel & Hautier (2016)	1741 ± 207	103.3 ± 11.8	Elite u-23	NS	peak during engagement phase	Artificial turf
Chapter 6	2254 ± 649	101.0 ± 14.1	Club amateur/university	160	peak	Natural turf
Chapter 7	2458 ± 455	103.0 ± 12.1	Club amateur/university	160	peak	Natural turf
Chapter 8	1720 ± 363	106.2 ± 13.3	University 1st XV	160	peak	Indoor

NS: Not specified within text

* calculated from percentage of average body mass and converted to force

Interaction between the feet and the turf

There was a big difference in the force magnitudes in the first two studies (Chapters 6 & 7) and in the third study (Chapter 8) which reported significantly smaller applied forces. The main difference between these studies was the surface of the ground. The third study was designed around an indoor rugby protocol and therefore the scrummaging assessments were conducted indoors on a hard floor surface, while the first two studies investigated the scrummaging kinetics outdoor with a rugby field surface. This comparison shows the effect of the turf on the scrummaging forces. While the different surface may allow for greater levels of friction, the reduction in the forces cannot be solely attributed to the interaction with the ground surface and one cannot determine whether the technical changes were present between the conditions. This was not the primary focus for the studies and warrants further investigation. Previous studies also testify to the interaction between the feet and ground, Morel et al., (2015) and Morel and Hautier (2016) used similar participants (playing level and age range) and showed greater forces when the scrummaging test was performed on artificial turf compared to a synthetic track (Table 9.1). There appears to be some influence of playing surface on force magnitude however further research is required utilising different population samples and methods of data acquisition. Future studies investigating the effects of the feet-turf interaction (various artificial turfs and natural turfs of varying composition) on scrummaging kinematics and force production are required.

Measuring the centre of pressure in individual scrummaging

The capability of the scrum ergometer used in Chapter 6 and 8 to measure the centre of pressure (CoP) is the first of its kind, to the author's knowledge. While previous research (Milburn 1990; du Toit et al., 2004; Preatoni et al., 2013) has shown the importance of the

force components, the studies within this thesis were the first to track the position of the exerted force during individual scrummaging. The CoP is the position of the force where all directional components will stem from. This position may prove important for individuals, specifically in the front row, as the individual contests within the scrum can ultimately determine the overall outcome of the scrum contest. By identifying the CoP position during scrummaging and applying knowledge regarding the magnitudes and directions of the force components, it may be possible to reduce scrum collapses and counteract scrum wheeling allowing for a safer and balanced contest. Subsequent analysis of the force CoP positions showed that positional specific differences were evident. Specifically, that front row players started scrummaging at a higher position and had less movement variation during the trial than back rows players. Front row players: exerted their maximal force at a higher vertical position; had lower variation in the CoP; and exhibited less movement to achieve their maximum force than the locks. It may be of interest to investigate the CoP position for the front row players as a group in an attempt to better contest scrums. Similarly the CoP position could possibly elucidate the development of overuse injuries in the front row players.

Kinematic evaluation of individual scrummaging

The sixth study (Chapter 7) specifically evaluated the kinematic contributors to individual scrummaging performance in tight five players. The study hypothesised, based on anecdotal suggestions, that a good base of support and a lower body position are related to scrummaging force magnitude. Additionally the study assessed more objective parameters, including joint angles of the legs and back straightness and lower body strength.

Scrum kinematics proved that the anecdotal advice of maintaining a lower hip position and wider base of support does assist in the generation of higher individual force. Both of these

variables contribute to stability and the maintenance of balance (Hrysomallis, 2011). Assuming that balance is required in the generation of force (through the provision of a stable platform from which to push), it could be inferred that the wider base of support allows for greater displacement of the centre of mass. Similarly the lower body position will allow for the greater upward movement and the ability to utilise additional muscle groups (greater muscle mass). Therefore the effects of balance ability may be a prolific area of investigation.

The assessment of the changes in limb kinematics during the scrummaging action suggests that multiple successful limb positioning strategies exist, rather than a single idealised body position. Sharp et al, (2014) reported the potential use of different strategies in the various playing levels, although no kinematic data was obtained. Their premise is largely due to the presence or absence of significant relationships between muscular groups, masses and the scrummaging forces.

Individual scrummaging performances of limb kinematics have failed to produce any significant relationships in the present studies. In addition and as reported in Chapter 1, Quarrie and Wilson (2000) and Wu and colleagues (2007) described similar values for individual scrummaging kinematics. Of these two studies only Wu and colleagues (2007) reported significant relationships with the body kinematics and scrummaging force. The major defining factor in the lack of relationships in the current study and Quarrie and Wilson (2000) may be the distinct yet varied posture that players assume when scrummaging. These postures have been ingrained into players as they are likely to the best approach to optimal performance and safety.

To accurately determine the strategies used in scrummaging a more holistic approach must be taken. The inclusion of electromyography and a higher recording frequency may shed light on the underlying determinants of scrummaging performance. Similarly the effects of

individual contributions within the scrum, both kinematics and kinetic require further investigation. The use of inertial monitors (Swaminathan et al., 2016) and other wireless kinematic system would allow for the investigations individual impacts and kinematics during a team scrum.

Scrummaging performance and match related fatigue

The final study of the thesis (Chapter 8) investigated whether simulated match induced fatigue could alter an individual's scrummaging technique and reduce their scrummaging performance. One of this study's hypotheses was that individual scrummaging performance, specifically the force magnitude, would decline following the simulation. Additionally it was expected that the scrummaging kinematics would be altered by the match protocol. The results indicated no reduction in the individual scrummaging forces. This result was surprising as Morel and colleagues (2015) reported a decrease in scrummaging force following repeated scrum efforts. The repeated scrums in conjunction with the fatigue developed during the rugby tasks and locomotion were expected to reduce the scrummaging forces. However more recent data from Morel and Hautier (2016) showed that peak scrummaging force may be unaffected by passive or active recovery during repetitive individual scrummaging. The Morel and Hautier (2016) study did however report that the standard deviation of the scrummaging force during the sustained phases was greater in the passive recovery group. The authors attribute the standard deviation of the sustained phase to increased instability in the scrum. These two studies lack the specificity of the development of fatigue. It is unlikely in the modern game to have six resetting of scrums, without a period of active recovery. One limitation of the current study (Chapter 8) was the exclusion of additional performance measures (sprint times, vertical jump heights, plyometric push-ups

etc.). The inclusion of one, or a combination of these tests, would have given further validation to the intensity of the fatigue protocol.

The results from chapter 8 indicate that the kinematics did not change as a result of the fatigue intervention. A possible reason for this may include the experienced training of the players and the distinct body postures involved in scrummaging. Additionally, as discussed in the preceding section, scrummaging technique may have a limited extent of posture variation. That is scrummaging can only be performed to a high level using a certain technical posture. An additional reason for the lack of kinematic differences may be the compensatory mechanisms to deal with the fatigue experienced, specifically those related to the large muscle groups of the back and lower limbs. The individuals may, when fatigued, recruit a different number of fibres to a greater effect and the degree of muscular activation of antagonistic muscles may increase. Further research required to investigate the effects of muscle fatigue on electromyographical and strength parameters.

The lack of differences in scrummaging performance raises the question as to why coaches substitute players when they do. It seems that coaches have a priori decision to change specifically their front row players around the 50-minute mark. The evidence would suggest that players may continue to sustain individual force for the length of a game. The standard deviation of the scrum sustained forces suggested increased scrum instability, although this has only been shown following repeated scrummaging efforts and not during a match (Morel and Hautier, 2016). Additionally the fluctuation of the sustained push may only cause instability within the competitive scrum if large force disparities are present. Therefore the effects of match fatigue are largely unanswered and require further investigations, specifically the assessment of electromyographical parameter.

9.4 The global perspective of performance arising from the collective performances of individuals

The scope of the current thesis is, strictly speaking, confined to a discussion of the abilities of individual rugby players to perform identified tasks (passing, kicking and scrummaging). In so doing, it is hoped that these measures relate to actual rugby performance, which can ultimately only be objectively measured as a relative score between teams which emerges once a match is complete. Although it is anticipated that these studies may act as foundational investigations for the ultimate understanding of rugby performance and reduce the vast gap between our current understanding of the ability of individuals to perform related tasks and actual performance, such a gap still exists. This chasm in knowledge between task success and the ability of a team to win a game of rugby is an under investigated topic, but one that is key to our understanding of performance in a complex game-system such as is the case for the game of rugby. While acknowledging that any attempt to singly answer this question is a fraught exercise, doing so is important and even necessary in order to give context to the data presented here and in many other studies of the ability of rugby players to perform specific actions, where rugby performance has been studied.

In order to link the individual technical ability of a player to a team's ultimate scoring ability I have proposed a larger model of team performance (Figure 9.1). Admittedly and unapologetically this model is a simple reflection of performance as I see it, where potential performance related tasks are identified and contextualised in a picture of global performance. Although I believe that this model serves well as a preliminary model, I have no doubt that if, studied further, better representations of performance may be found. That is, if empirical rigor is used, evaluation of the worthiness of alternative theoretical models can be made. Despite these a priori acknowledgements of the proposed model limitations, I feel it

is still necessary to contextualise the data (and the data from the many other studies which have used similar approaches to understanding rugby performance). To do this I first explain how a rugby team's performance is based on attacking and defensive strategies, where an attacking side has dual objectives of gaining territory and retaining ball position in order to allow for scoring. When defending however a team's performance will aim to gain ball possession and prevent the loss of territory, so as to prevent the loss of points. Hereafter I build the model of performance based on these principles, so that game events where either ball possession or field territory may be contested or traded off for strategic advantage. The next part of the performance model is related to the roles of both teams and individuals when engaging in these game events and thereby influence the game progression. The role of individual players is thereby related to the identified game events and the dynamics of team based factors is also accounted for. Once the role of the individual in the context of performance is established as described above it is possible to link individual performance to the ability to perform the identified performance related tasks. This also allows for the determinants of individual performance to be contextualised and potential factors related to the ability of an individual to perform to be identified. After the role of the individual and team have been related to the context of a positional and territorial model of rugby performance it is possible to relate the performance of one team to another. In the sections that follow I go through each of these steps building towards a proposed model of rugby performance. Following which, I explain the contributions of the studies of the current thesis in the context of the proposed model.

A proposed model of performance in rugby

In order to synthesise a model of rugby performance, it is first acknowledged that performance must relate to a team's ability to score points. The ability to score points is affected by the team's ball possession status, field territory and their ability to successfully perform an attacking play.

The model is divided into sections based on the contributions to the performance. The first section relates to the performance of the team, specifically their ability to score points. Once scoring events have been set as outcomes, a framework for the conditions for scoring (and the prevention of scoring by an opposing team) can be considered. It is my contention that scoring opportunities in rugby depend on the two main factors: the ability of a team to gain and retain ball possession and secondly for the team to move towards the opposing try line (or poles in the case of kicking points). Note that although ball possession is always necessary for scoring, territorial advantage is theoretically not (because it is theoretically possible for a single player to kick a drop goal from his own playing half). Despite this, for the purposes of all normal gameplay, both territorial gain and ball possession are needed to provide a scoring opportunity to a rugby team. Once the interplay of territorial progression and ball possession are considered in relation to their contributions to a team's potential scoring opportunity (or in their ability to prevent scoring by an opposing team, when a team is defending against scoring), a model of overall gameplay can be constructed. Such a model, that relates ball possession and field territory to scoring is therefore shown in figure 9.1.

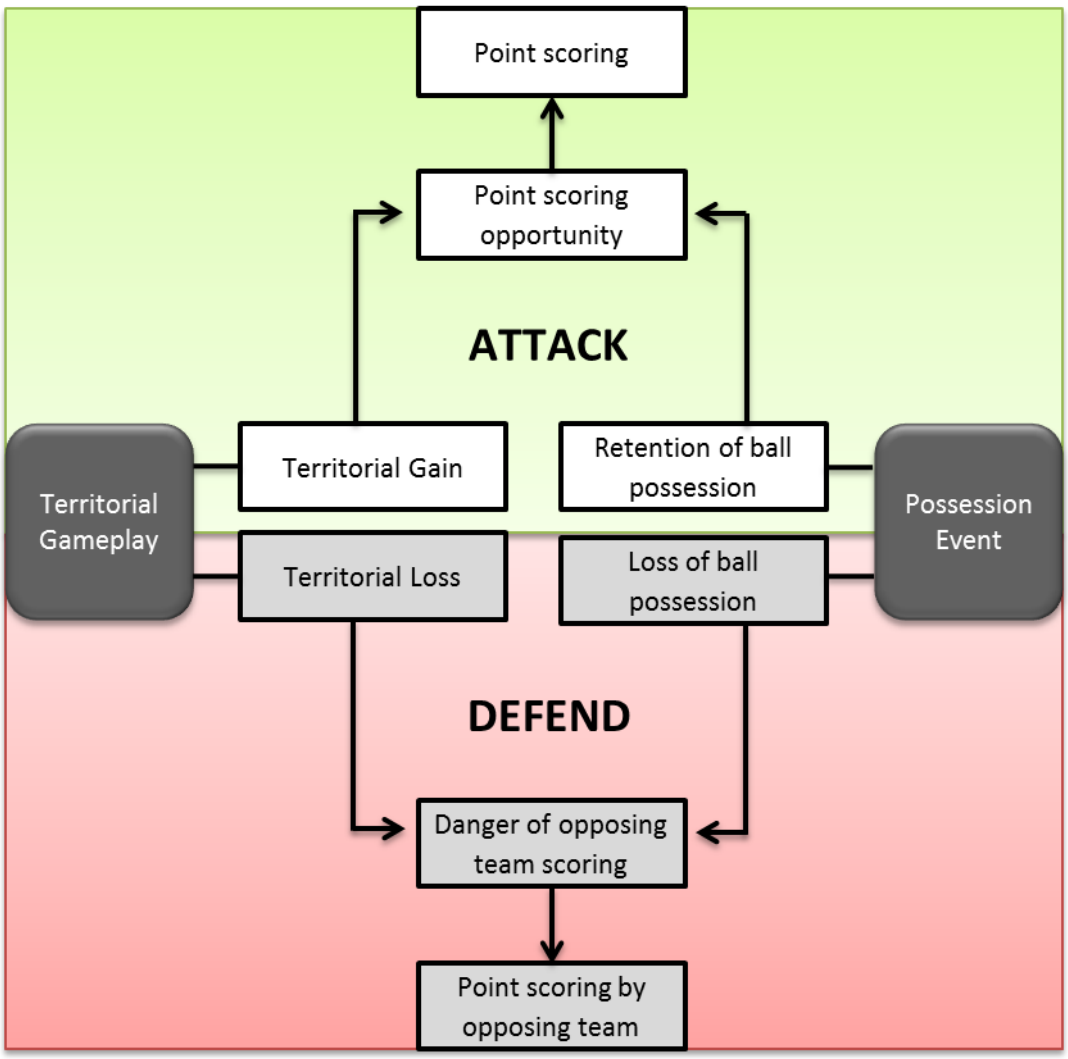


Figure 9.1: A model of the overall rugby gameplay based on field territory, ball possession, attacking and defending.

The success of a rugby team (ability of a team to score points) can be attributed to the combination of their field position and ball possession status (Figure 9.1). Note that such a model allows for gameplay to be characterised as either attacking or defensive, provided both conditions of territory and possession are considered. Events where possession and territory do not both support a team's scoring chances; for example, a kick that gains territory but loses possession; or a retreating scrum/maul which retains possession but gives up territory are unequivocal in respect of their scoring potential and so cannot rightly be considered either attacking or defensive. This combination of ball possession and field territory results allows

the potential of points scoring. Conversely a team is considered to be defending when they lack ball possession. By not having ball possession and favourable field position the defending team risk conceding points and will therefore either have to regain ball possession or drive their opponents backwards. The team with ball possession can choose between gaining field territory by either kicking the ball to set-up play in their opponent's half, or by running and passing the ball between players as they advance towards their opponents try line. The latter option is preferable as ball possession is maintained and can only be contested once a tackle has been made. By tackling the ball carrier, the defending team can contest for the ball in the tackle or during the resulting ruck or maul.

Once the above model has been established, it is possible to incorporate the events of rugby gameplay into this model and further expand the analysis of these events. Further expansion of the territorial game play section includes: kicking, running, mauling and scrummaging. These components of rugby can result in the gain or loss of field territory, depending on the execution of the task and to an extent the opposition's performances of these tasks (specifically the maul and scrum). In a similar way, the expansion of the possession events section includes: mauls; line-outs; kicks; scrums; rucks; tackles; and passes (Figure 9.2). All of the possession events may result in the retention or loss of ball possession.

The identification and analysis of these specific events within the game allows for a more discrete determination of performance within the team. This model has been applied to theoretical performances that assess the optimal methods to gain field territory and maintain ball possession. The simplest way for a team to gain territory for example would be for a player to run forward, while carrying the ball. Passing between players would usually cause small deficits in territorial gain (due to the requirement for passes to go backwards), but should facilitate further territorial progression and the retention of the ball by a team. Forward movement by combined units of players (scrums and mauls) would similarly result

in the gain in territory while retaining ball possession. A kick, while maximising the potential gain in field territory may result in the loss of ball possession. The decision for maximal field territory gain and retention of ball possession is a trade-off that the team will have to make. A poorly executed kick has the potential to cause both the loss of field territory and ball possession. The trade-off between territorial gains through kicking and the potential loss of ball possession is a constant dilemma for most teams and is a key element to the strategic efficacy of any team. retaining ball possession while acquiring a territorial gain leads to points scoring opportunities. Conversely, losing ball possession and field territory can potentially lead to the opposition scoring points.

A recent study of rugby league gameplay has identified the importance of field position in the scoring of points (Kempton et al., 2016). Teams that had possession closer to their opponents try line had a 33% chance of scoring points. The authors stressed that field position may not predict the scoring of points as rugby league is more complex than can be explained by field possession (Kempton et al., 2016). The increasing number of gameplay phases resulted in the reduction of points scoring opportunities. One of the differences between rugby league and union is the amount of phases or tackle that can occur before the loss of ball possession. In rugby league teams have five chances to beat the defensive line, upon the sixth tackle possession of the ball will be conceded to the defending team. For that reason, teams will normally kick the ball following the fifth tackle, to gain maximal field position. Conversely in rugby union there is no limit to the amount of phases or tackles the attacking team can have before conceding possession. Instead every tackle and breakdown is a contest for ball possession.

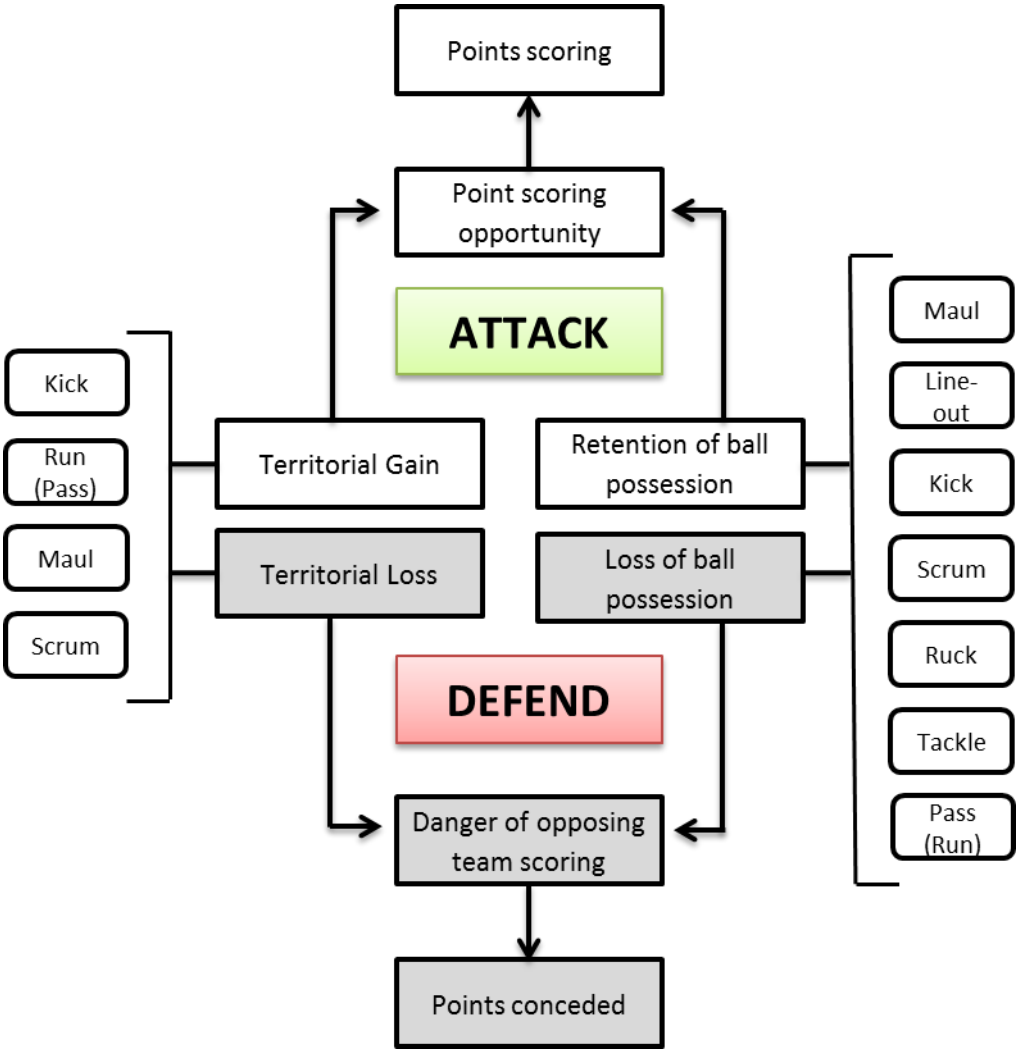


Figure 9.2: The inclusion of rugby gameplay tasks within the expanded model of rugby performance.

In the current model (Figure 9.2) presented for rugby union, field position, or territory, can be gained by kicking, scrummaging, passing, running or mauling. Scrummaging and mauling offer the least potential gain in territory, but most often result in retention of ball possession. Conversely kicking is potentially the method to gain the greatest advantage in field possession, but results in the loss of ball possession. Therefore the ideal way to gain field position while maintaining ball possession is through running and passing. Specific to the studies within this thesis, ball retention between passes may be determined by the passing strategy employed by the player. Contests for ball possession can result in either the loss or

retention of the ball. Possession can be contested in various tasks: the tackle; ruck; lineout; maul; and scrum. One of the contests for ball possession, the scrum, was amongst the performance assessments evaluated in this thesis. While the scrum performance was individually evaluated, the results of a lower body position and wider stance may relate to team scrummaging performance The performance of scrummaging in the context of this performance model will be discussed in the upcoming sections.

Not all contests for ball possession are fair, in the sense that teams may not have an equal opportunity to contest for the ball. That is teams may not be equal in their abilities to perform scrums and line-outs. Therefore teams may select to disproportionally perform tasks that are suited towards their strengths and the weaknesses of their opponents. The ability to score points, which is defined in this model as the overall performance of the team, is largely dependent on the team's playing strategy. Within the team's strategy may be certain aspects related to the territorial gameplay or ball possession contests. Similarly the team's ability to successfully attack and defend may play a role in their strategy. From the level of team strategy certain models within the team are identified, namely: team coordination; unit performance and individual performance. The interaction between individuals and units in the setting of the team is acknowledged through inter-individual coordination.

The performance model is mediated by the strategy of the team. Successful team strategy is to a large extend dependent on the ability of a team to make use of their own strengths and to identify and exploit the weaknesses of their opponents. The selected strategy is reliant on the coordination of the team, performance of units and individuals. Furthermore there are interactions between the performances of individuals and playing units within the overall coordination of the team (Figure 9.3).

Teams may select a strategy that exploits certain aspects of the trade-off between ball possession and territory. The selected strategy is dependent on the coordination within the team and the performances of playing units (Figure 9.3). That is, teams may choose to play a more territorial based game, through the use of kicking and line-outs, based on the strength of their line-out units, the hooker's ability to throw-in the ball and the accuracy of the kicks. Conversely (or in addition) teams may choose to contest ball possession events more often. The differing strategies are therefore reliant on the individual attributes (skill-based and physiologically) of the players. Specific to the technical assessments made within this thesis, teams may choose to: use running attacks with multiple passing sequences; kick at goals from further away and from more obtuse angles; contest more scrums, if their individual and unit scrum performances are superior to their opposition. A brief discussion of winning strategies used by Northern and Southern Hemisphere teams was presented in section 1.3.3.5.

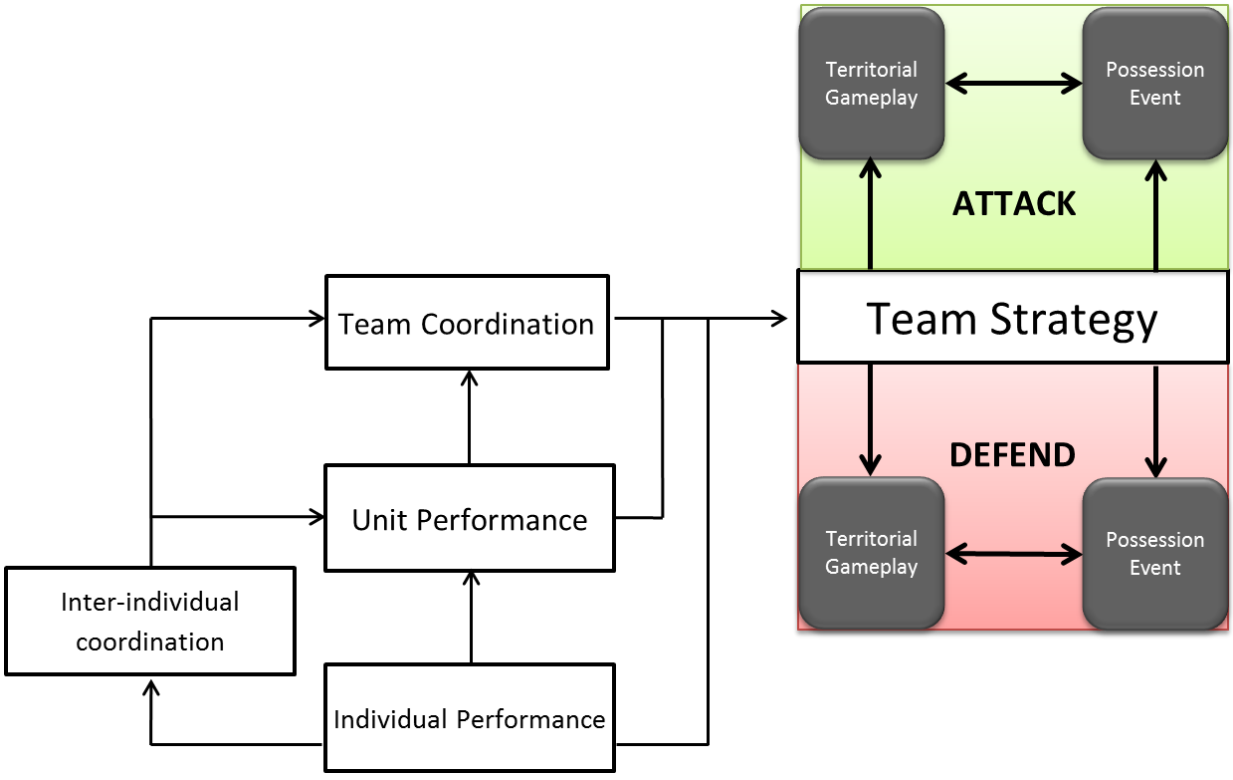


Figure 9.3: The rugby performance model defining the determinants of the team's playing strategy.

As described in Chapter 1, playing units are considered to be the interactions between individuals, such as in line-out lifting, mauling, and rucking. If each individual can optimise their performances and have effective inter-personal coordination, then unit performance can positively contribute to team performance. Inter-personal coordination requires synergy between individuals, such that the unit performance is greater than the sum of individual contributions. The coordination of the team is reliant on the unit performance and the coordination between individuals and units. The individual performance in this model is dependent on the skill (observed through a mental component and individual movement strategies) and physiological parameters.

The rapid nature of the game may warrant the change in gameplay (at the level of unit performance) which in turn would affect the team coordination. Furthermore, the environmental conditions may dictate as to how the dynamics within the units, and eventually the team, changes. That is, a rainy game may enforce a team to retain ball possession, through mauls and gain territory through out of hand kicks. Conversely, in dryer conditions teams (and units within teams) may choose to gain territory by running and retain ball possession through passing. Finally, the opposition may impose these changes by outperforming their opponents at the various tasks (lineouts, scrums, mauls).

One such example pertinent to the discussion is team scrummaging. Scrummaging performance, quantified in this thesis, was evaluated using compressive force. It must however be noted that scrummaging performance is not only determined by the ability of the team to generate and sustain large force magnitudes. To win or maintain ball possession the individual skill of the hooker to guide the ball towards the back row players is essential to securing the ball. The performance of the scrum is derived through the contributions of individuals, such that the team effort should be greater than the sum of the individuals. This in turn requires inter-personal coordination.

Additionally, performance of units that the model includes are: coordinative lifting (either during a line-out or from a restarting kick) and mauling. Specifically, the coordinative lifting requires a single player to jump into the air while one or more team mates supports them from the ground. This action requires the players to synchronise their movements in a way that optimises performance. While acting as a playing unit, the individuals involved in the coordinative lifting require the ability to catch (in the case of the lifted players), muscular strength (in the case of the supporting players), and refined dynamic control of balance (all players in the unit) to effect a successful lift. Regarding mauling, playing units within the team must coordinate their exerted forces in a manner that protects possession of that ball and allows the team to gain field territory. To achieve this the unit must remain tightly bound to one another, to reduce the loss of force magnitude, and produce the force in a coordinative effort similar to that of a team scrum.

The performances of the playing units are reliant on the performance of individuals. While individual performance may not directly affect the team's performance it is expected that collectively the sum of individual performances represents team performance. Focussing specifically on individual performance it is noted that to subjectively or objectively determine the performance requires knowledge of the positional demands as different rugby positions are highly specific (Jones et al., 2008). Previous contributors of individual performance have been categorised into technical, physiological and psychological aspects (Hughes and Bartlett, 2002). Therefore the current model (Figure 9.4) has adopted a similar approach utilising inputs from these aspects. Skill is defined as the combination of technical components (movement strategies) and psychological components (mental state), with the former being the major focus of the individual evaluations conducted in the current thesis.

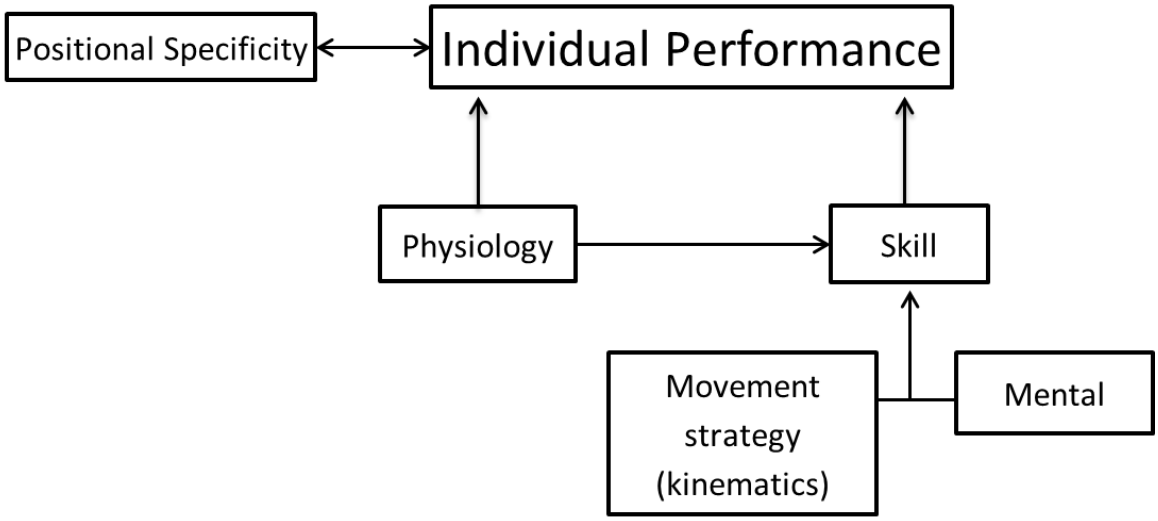


Figure 9.4: A model to define individual rugby performance in the context of skill (a combination of movement strategies and mental aspects) and physiological attributes.

Skill is what defines the motion and outcome and therefore is predominantly what coaches and scientists assess. The majority of individual performance parameters were identified and discussed in chapter 1. One particular example is the draw and pass which requires situational awareness and the correct sequence of movements to be effectively executed (Gabbett, Wake and Abernathy, 2011; Gabbett and Abernathy, 2012). Skills necessary to rugby irrespective of playing position include catching and jumping. These two skills are required in rugby to allow for continuous gameplay between phases, and therefore their inclusion into this performance model are compelled Another example, more specific to rugby, is the ability to tackle. The individual physical demands to complete an effective tackle and the situational awareness to tackle the correct individual is a crucial skill required for optimal individual performance. To the extent that Gabbett (2009) reported movement strategies that could be used to assess the performance of the tackle. The player's situational awareness may impact the performance of the tackle. Similarly a player that intends to kick requires the situational

awareness and competent technical skill (kinematics) to effectively perform the kick in open play.

Further refinement of the physiological, movement and mental components allows for easier analysis of the individual contributing constituents. The contribution of these constituents to the performance model will be discussed hereafter (Figure 9.5). The metabolic requirements of rugby require optimised and efficient aerobic and anaerobic metabolic systems. Aerobic and anaerobic capacity are necessary components for sports performance (see section 1.4.6.3) regardless of the model of performance. Balance and coordination are required in most tasks, not limited to the scope of sports performance. However the ability to balance (dynamically) while executing tasks is required by most athletes. The control of balance is essentially a physiological parameter as it is controlled by the neural system.

Neural control relates to the individual's ability to control limb segments and works in conjunction with segmental coordination. The combined effects of balance, coordination and neural control are largely understudied in sports and specifically in rugby. Strength is not limited to muscular strength but includes power and other factors reliant on strength in general such as sprinting. Most individual performance parameters are trainable however better players may have inherent qualities that distinguish them from other individuals.

The close and important interactions between physiological determinants of performance and movement strategies (balance, coordination, neural control, strength) can be considered the 'what' properties of skill. That is, they are the building blocks of the movement strategies which can be independently assessed and optimised. Similarly the other determinant of skill in this model refers to the mental or psychological ('when') component. This specifically relates to the situational awareness of the individual and their choice of tactics during the match.

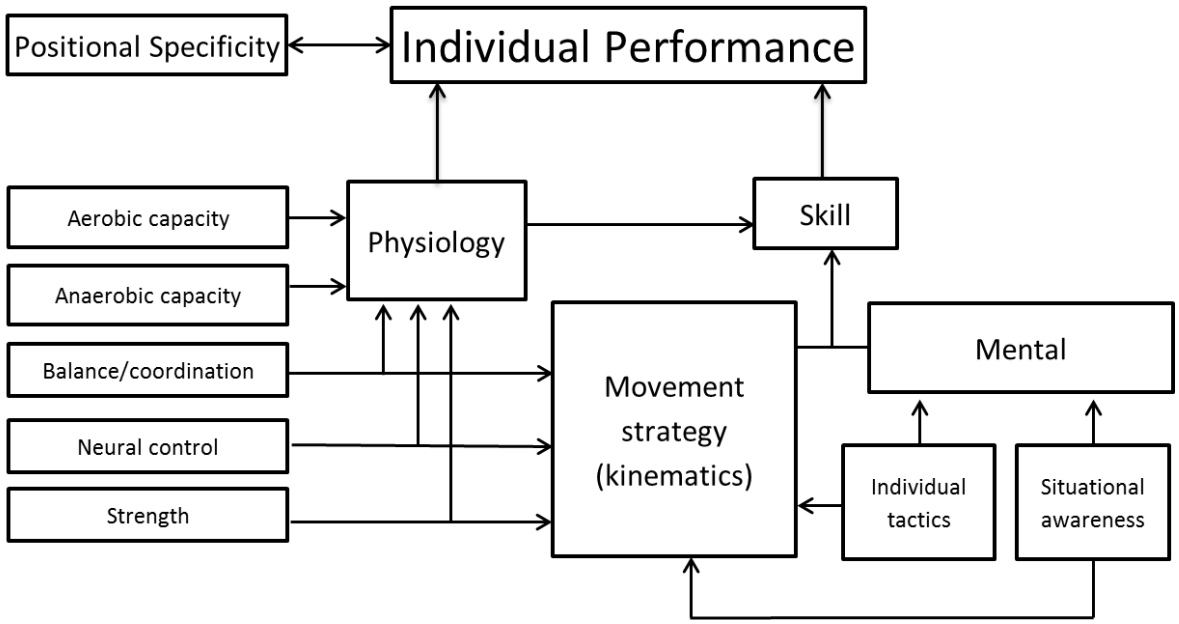


Figure 9.5: The expanded determinants of individual performance within the global model of rugby team performance.

The data emanating from the current thesis highlights the technical evaluation of individual tasks related to their specific performance outcomes. It is through the combination of the technical evaluations and performance outcomes which indicates the level of skill used to execute the task. Movement strategies in the current model are dependent on the physiological abilities and mental state of the individual. The physiological attributes are categorised into strength, balance, segmental and general coordination, and neural control. The mental state of the individual refers to their individual awareness, drawing from their situational awareness and individual tactics. The combination of the individual's mental state and movement strategies culminates in the observable skill.

It is noted that positional specificity is undoubtedly a contributing factor to the success of a team (Figure 9.5). However when selecting a team there may be an argument against

selecting 15 individual positional specific players compared to 15 players that can all execute the necessary tasks inherent to rugby. That is within the forwards all positions need to be able to pass, receive a pass (catch), run, tackle and then need to effectively perform specifics related to their positions (scrummages, lift in line-outs, rucks and mauls). Conversely the interaction between players of different roles may counter this argument. It is not possible for all players to be actively involved in the game at the same time (not all 15 players will contest a ruck, at the same time). Therefore the situational awareness and coordination between players may determine the task that the individual has to perform. Apart from set phases of the game (scrum, line-out and to an extent the maul) all players are required to contribute regardless of the task. To this end backs, whose role is largely dynamic running may be required to contest for the ball in the ruck. These overlapping tasks and their level of execution are what ultimately define individual performance in rugby.

The final component of the model relates to the match simulation that was used in chapter 8 to assess the effects of match related fatigue. Fatigue may not directly affect the team and therefore was included into this model at the level of individual performance. In this model fatigue is considered any reduction in performance as compared to the baseline (pre-match) values. Additionally fatigue can manifest at the three different indices of individual performance (Figure 9.6).

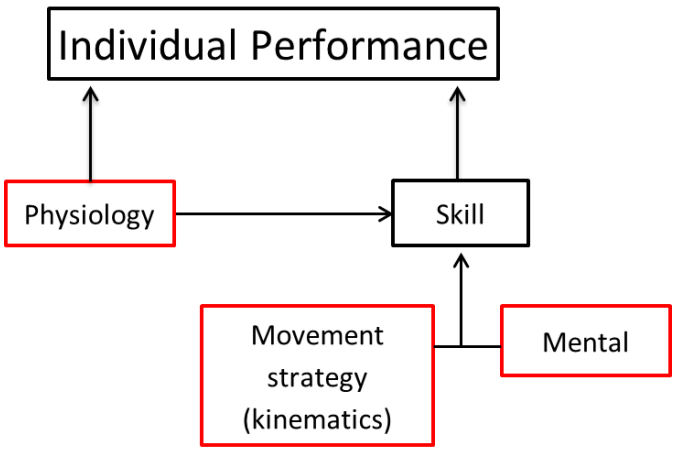


Figure 9.6: The manifestation of fatigue on physiological, movement and mental components of individual performance (represented by the red boxes).

In this model fatigue has been inserted at the level of individual performance, and can manifest at three different places: physiological, psychological and through the alteration of kinematics. The development of fatigue is inevitable through repeated efforts (sprints, tackles, scrums etc.). The resulting reduction in performance can result in the loss of territory or ball possession eventually leading to the conceding of points. Therefore, identifying fatigued players through reduced performance may be a better determinant for player substitution than a priori decisions. With that said the addition of 'fresh' players may prove to be advantageous over the opposition. However, it must be stressed that the effects of match related fatigue are poorly understood and are highly variable with respect to the individuals. Pertinent to the final study of the thesis (Chapter 8), no technical (kinematic) or performance (kinetic) parameters were changed following a simulated rugby match. Further research into the pacing of players within a game are required. It is acknowledged that a few studies have investigated pacing using GPS, but these studies lack information that reflects the technical performances of the players.

Each of the components of the model previously described are combined into a single model of rugby performance (Figure 9.7) which shows the complexities of rugby, from the level of

the individual to team strategies. The addition of knowledge from the studies within this thesis are in relation to the overall team performance have been identified in figure 9.7. It is acknowledged that while the contributions may be minor in the eventual result of the game, they do add to the understanding and foundation of technical performance in the context of rugby. Furthermore the studies within this thesis and the present model can be the base for larger and refined technical approaches to evaluating rugby performance. A plethora of research opportunities could result from these investigations and their interactions with a greater definition of rugby performance. A few potential future studies have been identified in the proceeding section.

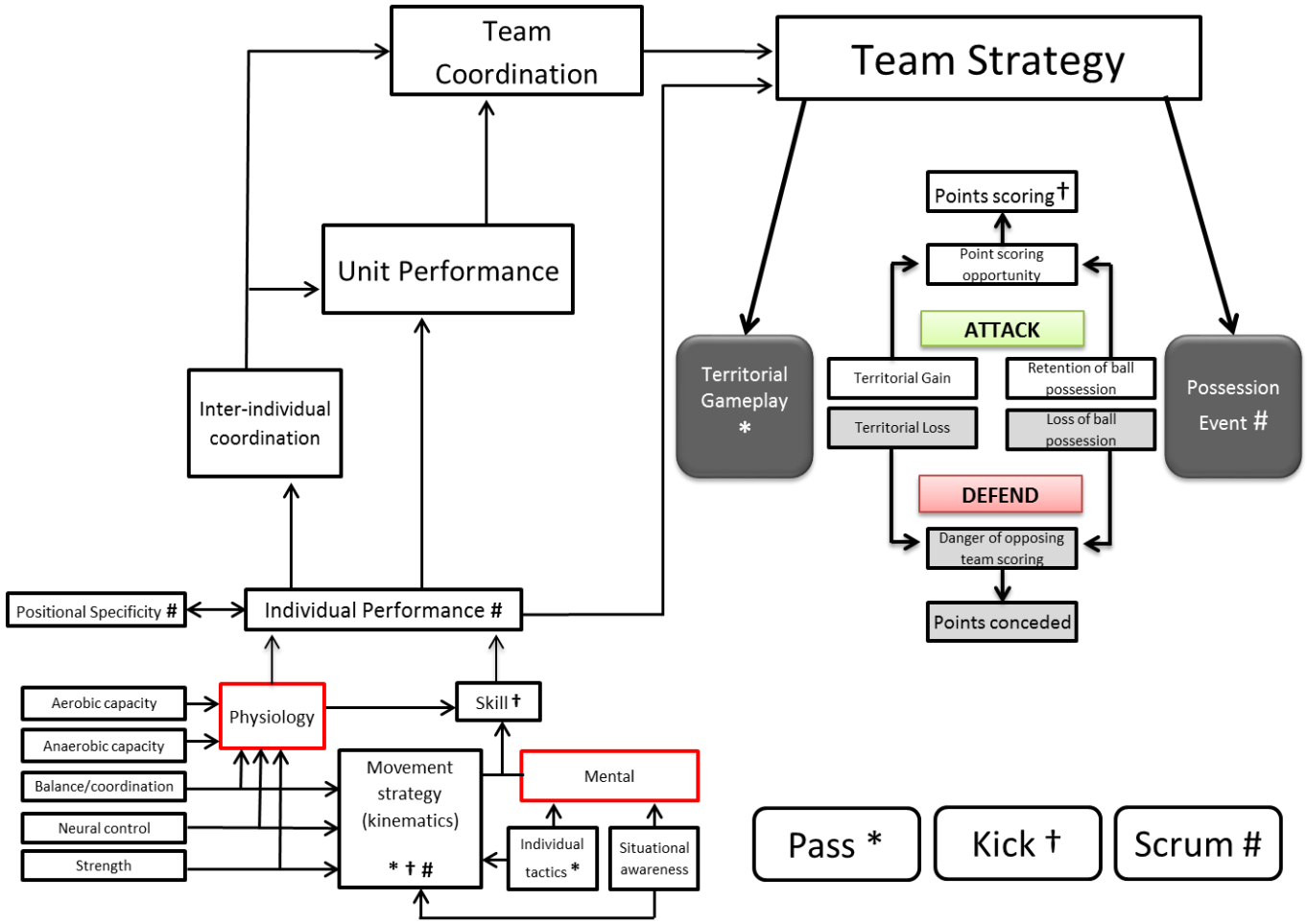


Figure 9.7: The combined model of rugby performance derived from individual performance. Key identifies the contribution of the studies (passing, kicking and scrummaging) within the current thesis. Physiological and mental fatigue have been identified, through the red blocks, under individual performance.

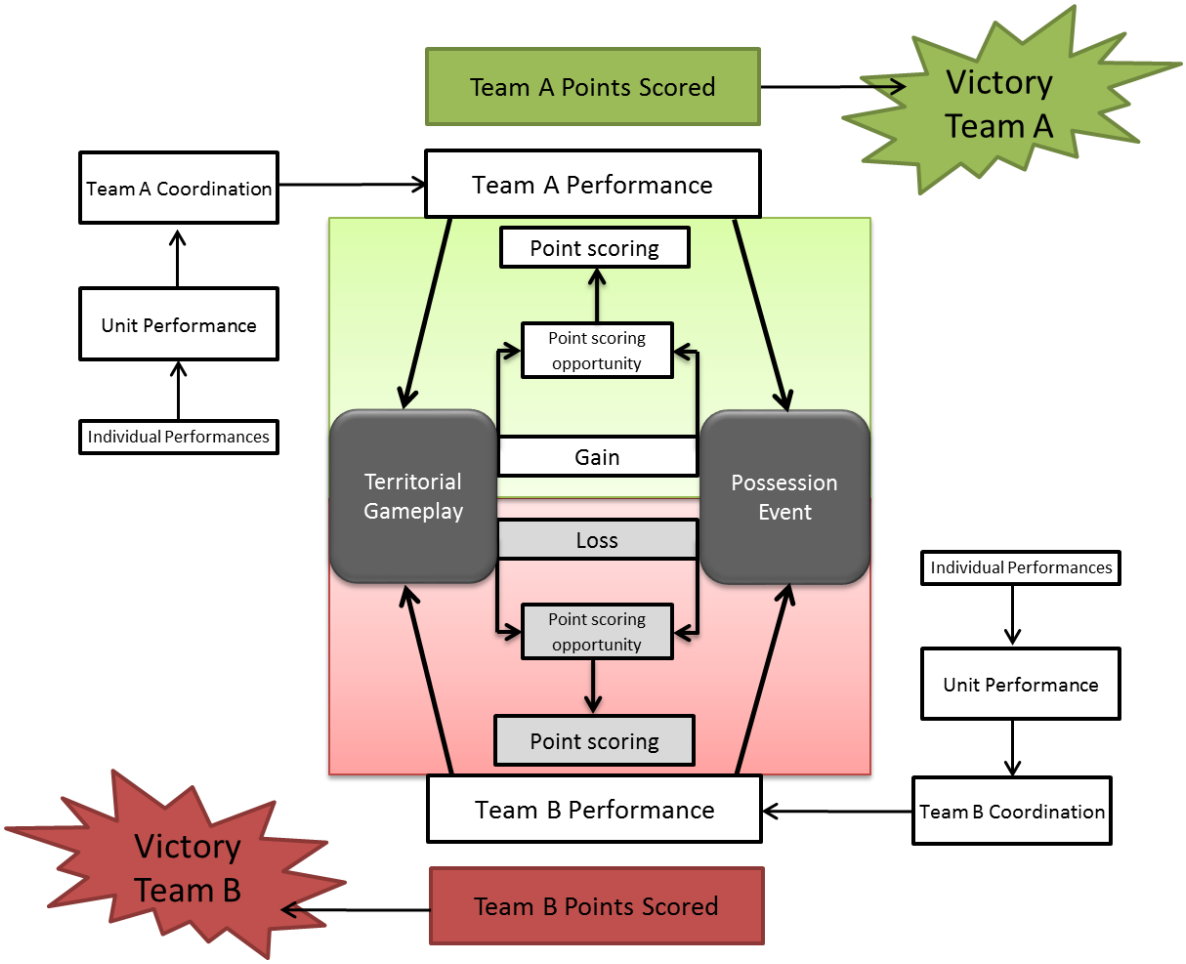


Figure 9.8: The interaction between opposing teams and the link between individual performance and point scoring in the model of rugby performance.

It should be noted that the single team performance model shown in figure 9.7 does not yet account for the performance of an opposing team and in order to account for the ultimate score (the ultimate objective measure of performance), the opposing team performance needs to be considered. Additionally the link between individual performance to final score is required. The obvious solution is to include the same scheme for the opposing team and since the proposed model already contains the relevant interactions in possession and territorial change, the opposing team performance can be easily incorporated as seen in figure 9.8. The model of rugby performance presented here lends itself to the interaction between opposing

teams. To win a game of rugby you have to out-compete your opponents in the specific tasks of the game and as shown in the previous sections, and at the various levels of the current model, there exists interplay between the two teams. The final part of the model is therefore to present the interactions between the two teams. The model displayed in figure 9.8 shows how the performances of teams A and B are interlinked. From the strategy of Team B it is necessary to optimally perform in their defensive efforts to stop Team A's advance into their territory and to potentially regain ball possession. Conversely it is Team A's strategy to gain field territory while maintaining ball possession in the attempt to score points.

How are previous studies included into the model?

While the model presented above was devised to better represent the performance in rugby from the level of the team down to the individual, it does agree with previously presented and inferred models of rugby performance (James et al., 2005; Jones et al., 2008; Ortega et al., 2009; Vaz et al., 2010; Hughes et al., 2012; Hendricks et al., 2015).

Previous assessments of performance have used notational analysis looking at the global level of team (James et al., 2005; Ortega et al., 2009; Vaz et al., 2010; Hughes et al., 2012) and individual performances (Jones et al., 2008). Notational analysis can be used to quantify the event but cannot determine their intentions or effectiveness. Information regarding the teams' strategies is needed. An example differing playing strategies can be identified in the studies by Ortega and colleagues (2009) and Vaz and colleagues (2010). The data presented in these studies (Ortega et al., 2009; Vaz et al., 2010) are incompatible as they highlight different parameters between winning and losing teams. The different parameters may be an indication of the strategy employed by the winning teams. Furthermore assessing these winning teams may dilute specific strategies for the more global determination of point differences. One

confounding factor in the Vaz et al. (2010) study was that only closely contested games (less than 11 points difference between the teams) were used in their analysis. It must be stressed that these parameters may in fact differentiate between winning and losing sides for the observed games, but they surely cannot predict game outcomes.

Hendricks and colleagues (2015) in their review of skill assessments in rugby (league and union) recommended the use of set criteria to determine the skill levels of individuals. The use of skill specific criteria was applied to rugby league players in their performances of the 'draw-and-pass' and tackling ability. These criteria may be applied to deterministic models which could possibly determine the defining features of skill performance. Furthermore, the use of deterministic models to quantify technical skill would allow for a continuum of performance instead of the usual binomial rating as suggested by Hendricks et al. (2015).

Concluding remarks of the performance model

The complexity of rugby gameplay demands the reduced nature of skill assessment (Hughes et al., 2012; Hendricks et al 2015). That is the evaluation of skills consisting of various numbers of players and individual players. The lowest strata would be the assessment of the individual (ball-carrier vs defender). I believe that the presented model has the capacity to evaluate performance from the level of the individual, through to smaller groups and culminates in the overall team performance.

This model is the first to my knowledge that assesses performance at multiple levels of the team. Through the application of the performance model presented here it is possible to link the determinants of individual performance to the eventual outcome of the game. The presented model allows for the assessment of performance at multiple levels of the team and

encompasses various aspects of performance. It must be stressed that the model has not undergone the rigors of peer-review and is ultimately based on my personal views. However the model is in agreement with other models and suggestions of authors in the literature. I firmly standby this model of performance as I believe it allows for the development of additional studies and investigation of performance within rugby. The development of the model was necessary to contextualise the studies within this thesis with the larger body of work that currently exists.

9.5 Study limitations

The limitations of the current studies include the use of simplified field tests and the capturing frequencies of the kinematic and kinetic systems. Ideally the frequency of the kinematic system should have been higher, especially for dynamic tasks of passing and kicking. While these studies may have been limited by the technical capabilities of the equipment, they are strengthened by their ecological validities. An additional limitation of the studies was the sample of university/amateur players. As a result, the current finding may only be applicable in this population and may not be applicable in more elite playing groups.

The lack of relationships exhibited in some of the studies could be due to the simplified nature of the field test (vertical jump) or the sample population of the participants. The very nature of rugby requires players to be physical fit with developed muscular strength (Duthie et al., 2003). Furthermore the lack of relationships between kick distance or accuracy and strength may relate to the activation of muscles and not the size of quantity of muscle fibres (Hart et al., 2014; Scurr et al., 2011). Regarding the relationship between scrummaging performance and muscular strength, previous studies that have identified relationships with more specific strength and endurance tests and individual scrummaging performance (Quarrie

and Wilson, 2000; Sharp et al., 2014). Therefore more complex laboratory based measures of muscular strength may be associated with kicking and scrummaging performance, which were not directly measured here. A specific limitation to the scrummaging studies, is the use on unidirectional load cells (only capable of measuring the compression force). Tri-axial load cells would give more information, specifically relating to the force components and directions. There may however be a population limitation regarding the strength of rugby players. Lovell and colleagues (2013) showed that rugby league players are generally stronger, and exhibit larger limb segments compared to physical active non-rugby players.

The majority of the studies within this thesis have assessed technical parameters through correlations with their respective performance outcomes. While it must be stressed that correlations do not imply causation, they do allow for the identification of potentially important factors related to performance. The envisaged studies that follow are required to test the validity of these findings. Should these finding be independently confirmed their application into training regimes is warranted, provided that the ability to train these variables improve performance outcomes.

9.6 Future studies following from this thesis

Overall the validation and repeatability of current findings in other and larger sample populations is warranted. The potential for future investigations emanating from this thesis is vast. A few potential ideas have been identified within the general discussion, but it is worth noting these again here, in more detail.

Quantification and evaluation of different passing strategies during matches to assess the outcomes and the effects of different passing strategies during matches. Particular attention should be placed on the phase of play and the interactions between the ball carrier and

intended receiver. It is envisaged that running velocities recorded via GPS units in conjunction with video footage would provide the necessary data for such an investigation.

The second potential series of studies are related to the interaction between the foot and ball during rugby kicking. These studies would not be limited to the place or drop kicks, but would be a broad investigation of all kicks in rugby. The interaction between the foot and the ball is essential to understanding the degree of control that players have when imparting energy onto the ball. This investigation may differentiate between the place and drop kicks. Similarly the effects of different kicking angles must be assessed in rugby place kicking. The combination of changing the kicking angle and evaluation of the ball and foot interactions may allow for the determination and control of kicking shapes.

In light of the finding of Chapters 6 and 7 the assessment of individual kinematics during a full scrum is warranted. The development of wearable kinematic devices would allow for segmental angles to be determined during team scrummaging. This assessment would serve as the 'litmus test' for further investigations into individual scrummaging performance.

9.7 Conclusion

The results of the current series of investigations within this thesis suggests that general performance of rugby players in a task not dependent on playing position (the running pass) showed a similar degree of accuracy despite the identification and use of numerous movement strategies. The ground pass accuracy was affected by the strategy used to complete the passes. The distance of place kicks can be optimised by increasing torso rotations and a technical trade-off between kick distance and accuracy may be present. The techniques used to perform the place and drop kicks are not dissimilar however minor differences are observed in the early phases of the kicking sequence. Performance in rugby's most unique

feature, the scrum, is dependent on the centre of mass position and the size of the base of support. Individual match simulated fatigue may have limited effect on scrummaging performance and techniques. Overall the identification of performance related factors and the invalidation of others which have been identified in the chapters of this thesis provide potential opportunities for the tailoring of training strategies for individual players and teams. Additionally the consequences of the body of work may result in better selection criteria for teams. However, these studies represent the preliminary set of studies and many of these factors still require the necessary validation and reassessment by subsequent research. Consequently the work within this thesis has provided a base for multiple research possibilities for later studies. A suggested topic of ensuing research may be to assess the repeatability of predictive power of the variables identified here. Specifically whether identified variables are uniformly predictive in different subject groups and finally whether theses individual performances are translatable into team performance.

In conclusion, the series of studies within this thesis addressed a number of objectives in order to assess the technical performance of individual rugby union players. Passing accuracy was shown for the first time to be dependent on the strategy employed. The place kick performance was dependent on the degree of torso axial rotation, but technically not different from the drop kick. The application of a novel and accurate individual scrummaging ergometer: endorsed a lower body position and wider stance width; and reported the preservation of scrummaging force magnitudes following a simulated match. Therefore the series of studies within this thesis have identified and evaluated technical parameters related to individual rugby performance.

The game of rugby is by far one of the most complex games currently contested. The complexity stems from the various roles that the different players on the field must perform. These specialised tasks may determine the strengths and weaknesses and therefore the

strategies that teams may employ. The dynamic gameplay of rugby allows for the strengths of one team to be negated by their opponents, which makes it a fascinating game. The popularity of rugby has surged over recent years with the unpredictable nature of the game being a major selling point. However these complexities provide challenges to sport scientists and performance analysists, as there is no simple way to understand or quantify performance. By simplifying the complexities of individual performance within a rugby team, and their relationships to team performance, should allow for improved team efficacy. This makes research into sports performance and specifically rugby fertile ground for future studies. The contributions of the current thesis are anticipated to act as the seeds from which further knowledge of individual technical performance may blossom.

Chapter 10:

References

Abdel-Aziz, Y.I. & Karara, H.M. Direct linear transformation from comparator coordinates into object space coordinates. ASP Symp. Close-Range Photogrammetry, (1971), University of Illinois, Urbana, III., pages 1-18.

Achten, J. & Jeukendrup, AE. (2003). Heart Rate Monitoring Applications and Limitations. *Sports Medicine*, 33(7): 517-538.

Allison, L. & MacLean, R. (2012). There's a Deathless Myth on the Close Tonight: Re-assessing Rugby's Place in the History of Sport. *The International Journal of the History of Sport*, 29(13): 1866-1884.

Andersson, H., Raastad T., Nilsson J., Paulsen G., Garthe I. & Kadi F. (2008). Neuromuscular Fatigue and Recovery in Elite Female Soccer: Effects of Active Recovery. *Medicine & Science in Sports & Exercise,* 40(2): 372-380.

Andrew, M., Grobbelaar, H.W. & Potgieter J.C. (2007). Sport psychological skill levels and related psychosocial factors that distinguish between rugby union players of different participation levels. *South African Journal for Research in Sport, Physical Education and Recreation*, 29(1): 1-14.

Apriantono, T., Nunome, H., Ikegami, Y. & Sano, S. (2006). The effect of muscle fatigue on instep kicking kinetics and kinematics in association football. *Journal of Sports Sciences,* 24: 951-960.

Asai, T., Carré, M. J., Akatsuka, T. & Haake, S.J. (2002). The curve kick in football I: impact with the foot. *Sports Engineering*, 5: 183-192.

Assi, H.N. & Bottoms, L. (2014). The effects of caffeine on rugby passing accuracy while performing the Reactive Agility Test. *Science & Sports*, 29: 275-281.

Atkins, S.J. (2005). Performance of the Yo-Yo Intermittent Recovery Test by elite professional and semiprofessional rugby league players. *Journal of Strength and Conditioning Research,* 19(4): 222-225.

Austin, D., Gabbett, T. & Jenkins, D. (2011). Repeated high-intensity exercise in professional rugby union. *Journal of Sports Sciences*, 29(10): 1105-1112.

Austin, D.J., Gabbett, T.J. & Jenkins, D.G. (2013). Reliability and sensitivity of a repeated high-intensity exercise performance test for rugby league and rugby union. *Journal of Strength and Conditioning Research*, 27(4): 1128– 1135.

Azidin, R.M.F.R., Sankey, S., Drust, B., Robinson, M.A. & Vanrenterghem, J. (2015). Effects of treadmill versus overground soccer match simulations on biomechanical markers of anterior cruciate ligament injury risk in side cutting. *Journal of Sports Sciences*, 33(13): 1332-1341.

Azizbeigi, K., Atashak, S. & Stannard, S.R. (2015). Effect of different rest interval lengths of resistance exercise on lipid peroxidation and creatine kinase responses. *Kinesiology*, 47(2): 139-144.

Baker, D. (1996). Improving Vertical Jump Performance Through General, Special, and Specific Strength Training: A Brief Review. *Journal of Strength and Conditioning Research,* 10(2): 131-136.

Baktash, S., Hy, A., Muir, S., Walton, T. & Zhang, Y. (2009). The effects of different instep foot positions on ball velocity in place kicking. *International Journal of Sports Science and Engineering*, 3(2): 85-92.

Ball, K. (2010). Kick impact characteristics for different rugby league kicks. In: Jensen, R., Ebben, W., Petushek, E., Richter, C. & Roemer, K. (Eds). International Conference on Biomechanics in Sports 458-461. Germany.

Ball, K., Talbert, D. & Taylor, S. (2013). Biomechanics of goal-kicking in rugby league. In Nunome, H., Drust, B. & Dawson, B., (Eds). Science and Football VII 47-52. New York: Routledge.

Bangsbo, J. (1994). Energy demands in competitive soccer. *Journal of Sports Sciences*, 12: 5-12.

Barr, M.J., Sheppard, J.M., Gabbett, T.J. & Newton, R.U. (2015). The Effect of Ball Carrying on the Sprinting Speed of International Rugby Union Players. *International Journal of Sports Science & Coaching,* 10(1): 1-9.

Bauer, T. & Vincent, J. (2015). Rugby, Modernity and Controversy: Le P'tit Parigot (1926) by René Le Somptier. *Sport in History*, 1-17. doi:10.1080/17460263.2015.1089315.

Beneke, R. (2015), Rugby Football: Fascinating Sport, Exceptional History and Developments, Immense Potential for Research. *International Journal of Sports Physiology and Performance*, 10: 673.

Berger, B.G. & Motl, R.W. (2000). Exercise and mood: A selective review and synthesis of research employing the profile of mood states. *Journal of Applied Sport Psychology*, 12(1): 69-92.

Bezodis, N., Trewartha, G., Wilson, C. & Irwin, G. (2007). Contributions of the non-kicking-side arm to rugby place-kicking technique. *Sports Biomechanics*, 6(2): 171-186.

Borg, G. (1970). Perceived exertion as an indicator of somatic stress. *Scandinavian Journal of Rehabilitation Medicine,* 2(2): 92-98.

Borg, G. (1982). Psychophysical bases of perceived exertion. *Medicine and Science in Sports and Exercise*, 14(5): 377-381.

Brancaccio, P., Maffulli, N. & Limongelli, F.M. (2007). Creatine kinase monitoring in sport medicine. *British Medical Bulletin*, 81 and 82: 209-230.

Brooks, J.H., Fuller, C.W., Kemp, S.P. & Reddin, D.B. (2008). An assessment of training volume in professional rugby union and its impact on the incidence, severity, and nature of match and training injuries. *Journal of Sports Sciences,* 26: 863-873.

Brown, J.C., Lambert, M.I., Verhagen, E., Readhead, C., van Mechelen, W. & Viljoen, W. (2013). The incidence of rugby related catastrophic injuries (including cardiac events) in South Africa from 2008 to 2011: a cohort study. *British Medical Journal Open* 3: e002475. doi:10.1136/ bmjopen-2012-002475.

Cahill, N., Lamb, K., Worsfold, P., Headey, R. & Murray, S. (2013). The movement characteristics of English Premiership rugby union players. *Journal of Sports Sciences,* 31(3): 229-237.

Campo, M., Champely, S., Lane, A.M., Rosnet, E., Ferrand C. & Louvet, B. (2016). Emotions and performance in rugby. *Journal of Sport and Health Science,* (in Press) 1-7.

Cazzola, D., Preatoni, E., Stokes, K., England, M.E. & Trewartha, G. (2014). A modified prebind engagement process reduces biomechanical loading on front row players during scrummaging: a cross-sectional study of 11 elite teams. *British Journal of Sports Medicine,*1-6. doi:10.1136/bjsports-2013-092904.

Cazzola, D., Stone, B., Holsgrove, T.P., Trewartha, G. & Preatoni, E. (2015). Spinal muscle activity in simulated rugby union scrummaging is affected by different engagement conditions. *Scandinavian Journal of Medicine and Science in Sports*, 1-9 doi: 10.1111/sms.12446

Charnock, B.L., Lewis, C.L., Garrett Jr, W. E. & Queen, R.M. (2009). Adductor longus mechanics during the maximal effort soccer kick. *Sports Biomechanics,* 8(3): 223-234.

Chew-Bullock, T.S.Y., Anderson, D.I., Hamel, K.A., Gorelick, M.L., Wallace, S.A. & Sidaway, B. (2012). Kicking performance in relation to balance ability over the support leg. *Human Movement Science,* 31(6): 1615-1623.

Chow, J.W. & Knudson, D.V. (2011). Use of deterministic models in sports and exercise biomechanics research. *Sports Biomechanics,* 10(3): 219-233.

Chu, Y., Sell, T.C. & Lephart, S.M. (2010). The relationship between biomechanical variables and driving performance during the golf swing. *Journal of Sports Sciences,* 28: 1251-1259.

Cockcroft, J. & van den Heever, D. (2016). A descriptive study of step alignment and foot positioning relative to the tee by professional rugby union goal-kickers. *Journal of Sports Sciences,* 34(4):321-329.

Coutts, A.J., Rampinini, E., Marcora, S.M., Castagna, C. & Impellizzeri, F.M. (2007a). Heart rate and blood lactate correlates of perceived exertion during small-sided soccer games. *Journal of Science and Medicine in Sport,* 12(1):79-84.

Coutts, A.J., Reaburn, P., Piva, T.J. & Rowsell, G.J. (2007b). Monitoring for overreaching in rugby league players. *European Journal of Applied Physiology*, 99(3): 313-324.

Croft, H., Chong, A. & Wilson, B. (2011). Virtual reality assessment of rugby lineout throw kinematics. *Sports Technology,* 4(1): 2-12.

Cummins, C., Orr, R., O'Connor, H. & West, C. (2013). Global Positioning Systems (GPS) and Microtechnology Sensors in Team Sports: A Systematic Review. *Sports Medicine,* 43: 1025-1042.

Cunniffe, B., Proctor, W., Baker, J.S. & Davies, B. (2009). An evaluation of the physiological demands of elite rugby union using GPS tracking software. *Journal of Strength and Conditioning Research,* 23(4): 1195-1203.

Currell, K. & Jeukendrup, A.E. (2008). Validity, Reliability and Sensitivity of Measures of Sporting Performance. *Sports Medicine,* 38(4): 297-316.

de Leva, P. (1996). Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. *Journal of Biomechanics,* 29: 1223-1230.

DeMello, J.J., Cureton, K.J., Boineau, R.E. & Singh, M.M. (1987). Ratings of perceived exertion at the lactate threshold in trained and untrained men and women. *Medicine & Science in Sports & Exercise,* 19(4): 354-362,

Dempster, W.T. & Gaughran, G.R.L. (1967). Properties of body segments based on size and weight. *American Journal of Anatomy,* 120: 33-54.

Deutsch, M.U., Kearney, G.A. & Rehrer, N.J. (2007). Time- motion analysis of professional rugby union players during match-play. *Journal of Sports Sciences,* 25(4): 461-472.

Deutsch, M.U., Maw, G. J., Jenkins, D., & Reaburn, P. (1998). Heart rate, blood lactate and kinematic data of elite colts (under-19) rugby union players during competition, Journal of Sports Sciences, 16(6): 561-570.

Dichiera, A., Webster, K.E., Kuilboer, L., Morris, M.E., Bacha, T.M. & Feller, J.A. (2006). Kinematic patterns associated with accuracy of the drop punt kick in Australian Football. *Journal of Science and Medicine in Sport,* 9: 292-298.

Dimitropoulos, P.E. & Limperopoulos, V. (2014). Player contracts, athletic and financial performance of the Greek football clubs. *Global Business and Economics Review*, 16(2): 123-141.

Diniz, A., Barreiros, J. & Passos, P. (2014). To Pass or Not to Pass: A Mathematical Model for Competitive Interactions in Rugby Union. *Journal of Motor Behavior*, 46(5): 293-302.

Doherty, M., Smith, P. M., Hughes, M. G. & Collins, D. (2001). Rating of perceived exertion during high-intensity treadmill running. *Medicine & Science in Sports & Exercise*, 33(11): 1953-1958.

du Toit, D.E., Olivier, P.E. & Buys, F.J. (2005). Kinetics of full scrum and staggered scrum engagement in under-19 schoolboy rugby union players. *South African Journal for Research in Sport, Physical Education and Recreation,* 27: 15-28.

du Toit, D.E., Venter, D.J.L., Buys, F.J. & Olivier, P.E. (2004). Kinetics of rugby union scrummaging in under-19 schoolboy rugby forwards. *South African Journal for Research in Sport, Physical Education and Recreation,* 26: 33-50.

Duffield, R., Murphy, A., Snape, A., Minett, G.M. & Skein, M. (2012). Post-match changes in neuromuscular function and the relationship to match demands in amateur rugby league matches. *Journal of Science and Medicine in Sport,* 15: 238-243.

Durandt, J., du Toit, S., Borresen, J., Hew-Butler, T., Masimla, H., Jakoet, I. & Lambert, M. (2006). Fitness and body composition profiling of elite junior South African rugby players. *South African Journal of Sports Medicine,* 18(2): 38-45.

Duthie, G., Pyne, D. & Hooper, S. (2003). Applied Physiology and Game Analysis of Rugby Union. *Sports Medicine*, 33(13): 973-991.

Duthie, G., Pyne, D. & Hooper, S. (2005). Time motion analysis of 2001 and 2002 super 12 rugby. *Journal of Sports Sciences*, 23(5): 523-530

Duthie, G.M., Pyne, D.B. Marsh, D.J. & Hooper, S.L. (2006). Sprint patterns in rugby union players during competition. *Journal of Strength and Conditioning Research*, 20(1): 208-214.

Elliott, B. (2006). Biomechanics and tennis. *British Journal of Sports Medicine*, 40: 392-396.

Enoka, R.M., Baudry, S., Rudroff, T., Farina, D., Klass, M. & Duchateau, J. (2011). Unraveling the neurophysiology of muscle fatigue. *Journal of Electromyography and Kinesiology*, 21: 208-219.

Erdmann, W. (1997). Geometric and inertial data of the trunk in adult males. *Journal of Biomechanics*, 30: 679-688.

Eston, R. (2012) Use of Ratings of Perceived Exertion in Sports. *International Journal of Sports Physiology and Performance*, 7: 175-182.

Eston, R.G. & Williams, J.G. (1988). Reliability of ratings of perceived effort regulation of exercise intensity. *British Journal of Sports Medicine*, 22(4): 153-155.

Fatouros, I.G., Chatzinikolaou, A., Douroudos, I.I., Nikolaidis, M.G., Kyparos, A., Margonis, A., Michailidis, Y., Vantarakis, A., Taxildaris, K., Katrabasas, I., Mandalidis, D., Kouretas, D. & Jamurtas, A.Z. (2010). Time-course of changes in oxidative stress and antioxidant status responses following a soccer game. *Journal of Strength and Conditioning Research*, 24(12): 3278-3286.

Finsterer, J. (2012). Biomarkers of peripheral muscle fatigue during exercise. *BMC Musculoskeletal Disorders,* 13:218 1-13. doi:10.1186/1471-2474-13-218.

Fitts, R.H. (2008). The cross-bridge cycle and skeletal muscle fatigue. *Journal of Applied Physiology,* 104: 551-558.

Flavell, C., Sayers, M.G.L., Gordon, S.J. & Lee, J.B. (2013). Mechanisms for triceps surae injury in high performance front row rugby union players: A kinematic analysis of scrummaging drills. *Journal of Sports Science and Medicine,* 12(1): 159-164.

Fleisig, G.S., Barrentine, S.W., Escamilla, R.F. & Andrews, J.R. (1996). Biomechanics of overhand throwing with implications for injuries. *Sports Medicine,* 21(6): 421-437.

Fousekis, K., Tsepis, E. & Vagenas, G. (2010). Lower limb strength in professional soccer players: profile, asymmetry, and training age, *Journal of Sports Science and Medicine,* 9: 364-373.

Frenzilli, R.J. III & Leighton, D. (1989). Sports performance series: A kinesiological description of the rugby spin pass and a rugby training program. *National Strength & Conditioning Association Journal,* 11(3): 6-13.

Froyd, C., Millet, G.Y. & Noakes, T.D. (2013). The development of peripheral fatigue and short-term recovery during self-paced high-intensity exercise. *Journal of Physiology,* 591(5): 1339-1346.

Fullenkamp, A.M., Campbell, B.M., Laurent, C.M. & Lane, A.P. (2015). The contribution of trunk axial kinematics to poststrike ball velocity during maximal instep soccer kicking. *Journal of Applied Biomechanics,* 31: 370-376.

Fuller, C.W., Brooks, J.H.M., Cancea, R.J., Hall, J. & Kemp, S.P.T. (2007). Contact events in rugby union and their propensity to cause injury. *British Journal of Sports Medicine*, 41: 862-867.

Fuller, C.W., Taylor, A.E., Brooks, J.H.M. & Kemp, S.P.T. (2013). Changes in the stature, body mass and age of English professional rugby players: A 10- year review. *Journal of Sports Sciences*, 31(7): 795-802.

Fuss, F.K., Masterton Smith, R. & Leali, F. (2013). Kick precision and spin rate in drop and torpedo punts. *Procedia Engineering*, 60: 448-452.

Gabbett, T.J. (2000). Physiological and anthropometric characteristics of amateur rugby league players. *British Journal of Sports Medicine*, 34: 303-307.

Gabbett, T.J. (2002). Physiological characteristics of junior and senior rugby league players. *British Journal of Sports Medicine*, 36: 334-339.

Gabbett, T.J. (2005). Changes in physiological and anthropometric characteristics of rugby league players during a competitive season. *Journal of Strength and Conditioning Research*, 19(2): 400-408.

Gabbett, T.J. (2008). Influence of fatigue on tackling technique in rugby league players. *Journal of Strength and Conditioning Research*, 22(2): 625-632.

Gabbett, T., Kelly, J. & Pezet, T.A (2008). Comparison of fitness and skill among playing positions in sub-elite rugby league players. *Journal of Science and Medicine in Sports*, 11(6): 585-592.

Gabbett, T.J. (2009). Physiological and anthropometrical correlates of tackling ability in rugby league players. *Journal of Strength and Conditioning Research*, 23(2): 540-548.

Gabbett, T.J., Jenkins, D.G. & Abernethy, B. (2011a). Correlates of tackle ability in high-performance rugby league players. *Journal of Strength and Conditioning Research*, 25(1): 72-79.

Gabbett, T.J., Jenkins, D.G. & Abernethy, B. (2011b). Relative importance of physiological, anthropometric, and skill qualities to team selection in professional rugby league. *Journal of Sports Sciences*, 29(13): 1453-1461.

Gabbett, T., Wake, M. & Abernathy, B. (2011). Use of dual-task methodology for skill assessment and development: Examples from rugby league. *Journal of Sports Sciences*, 29(1): 7-18.

Gabbett, T. & Abernathy, B. (2012). Dual-task assessment of a sporting skill: influence of task complexity and relationship with competitive performances. *Journal of Sports Sciences*, 30(16): 1735-1745.

Gabbett, T.J., Polley, C., Dwyer, D.B., Kearney, S. & Corvo, A. (2014). Influence of field position and phase of play on the physical demands of match-play in professional rugby league forwards. *Journal of Science and Medicine in Sport,* 17(5): 556-561.

Gabbett, T.J. (2015). The training-injury prevention paradox: should athletes be training smarter and harder? *British Journal of Sports Medicine,* 1-10. doi:10.1136/bjsports-2015-095788.

García, J.A., Sabido, R., Barbado, D. & Moreno, F.J. (2013). Analysis of the relation between throwing speed and throwing accuracy in team-handball according to instruction. *European Journal of Sport Science*, 13: 149-154.

Glazier, P.S. & Davids, K. (2009). Constraints on the complete optimization of human motion. *Sports Medicine*; 39(1): 15-28.

Glazier, P.S. & Robins, M.T. (2012). Comment on “Use of deterministic models in sports and exercise biomechanics research” by Chow and Knudson (2011). *Sports Biomechanics*; 11(1): 120-122.

Golby, J. &Sheard, M. (2004). Mental toughness and hardiness at different levels of rugby league. *Personality and Individual Differences*, 37(3) 933–942.

Grant, S.J., Oommen, G., McColl, G., Taylor, J., Watkins, L., Friel, N., Watt, I. & McLean, D. (2003). The effects of ball carrying method on sprint speed in rugby union football players. *Journal of Sports Sciences*, 21: 1009-1015.

Greenwood, J. (1997). Total rugby. London: A and C Black.

Grobbelaar, H.W., Mala, D.D.J., Steyn, B.J.M. & Ellis, S.M. (2011). The relationship between burnout and mood state among student rugby union players. *African Journal for Physical, Health Education, Recreation and Dance*, 17(4): 647-664.

Gutierrez, E.M., Bartonek, A., Haglund-Akerlind, Y. & Saraste, H. (2003). Centre of mass motion during gait in persons with myelomeningocele. *Gait and Posture,* 18: 37-46.

Gutierrez-Farewik, E.M., Bartonek, A. & Saraste, H. (2006). Comparison and evaluation of two common methods to measure center of mass displacement in three dimensions during gait. *Human Movement Science,* 25: 238-256.

Hart, N.H., Nimphius, S., Cochrane, J.L. & Newton, R.U. (2013). Leg mass characteristics of accurate and inaccurate kickers-an Australian football perspective. *Journal of Sports Sciences*, 31: 1647-1655.

Hart, N.H., Nimphius, S., Spiteri, T. & Newton, R.U. (2014). Leg strength and lean mass symmetry influences kicking performance in Australian football. *Journal of Sports Science and Medicine*, 13: 157-165.

Harvey, A. (2013). The emergence of football in nineteenth-century England: The historiographic debate. *The International Journal of the History of Sport*, 30(18): 2154-2163.

Hawkins, M.N., Raven, P.B., Snell, P.G., Stray-Gundersen, J. & Levine, B.D. (2007). Maximal oxygen uptake as a parametric measure of cardiorespiratory capacity. *Medicine & Science in Sports & Exercise*, 39(1):103-107.

Helgerud, J., Engen, L.C., Wisløff, U. & Hoff, J. (2001). Aerobic endurance training improves soccer performance. *Medicine & Science in Sports & Exercise*, 33(11): 1925-1931.

Hendricks, S., Karpul, D., Nicholls, F. & Lambert, M. (2012). Velocity and acceleration before contact in the tackle during rugby union matches. *Journal of Sports Sciences*, 30(12): 1215-1224.

Hendricks, S., Lambert, M., Masimla, H. & Durandt, J. (2015). Measuring skill in rugby union and rugby league as part of the standard team testing battery. *International Journal of Sports Science & Coaching*, 10(5): 949-965.

Herrington, L. & Horsley, I. (2009). Electromyographic analysis of selected shoulder muscles during a rugby football tackle. *Sports Medicine, Arthroscopy, Rehabilitation, Therapy & Technology*, 1(10): 1-10.

Higgins, T.R., Cameron, M.L. & Climstein, M. (2013). Acute response to hydrotherapy after a simulated game of rugby. *Journal of Strength & Conditioning Research* ,27(10): 2851-2860.

Higham, D.G., Hopkins, W.G., Pyne, D.B. & Anson, J.M. (2014). Performance indicators related to points scoring and winning in international rugby sevens. *Journal of Sports Science and Medicine,* 13: 358-364.

Highton, J., Twist, C., Lamb, K. & Nicholas, C. (2013). Carbohydrate-protein coingestion improves multiple-sprint running performance. *Journal of Sports Sciences*, 31(4): 361-369.

Hohmann, T., Obelöer, H., Schlapkohl, N. & Raab, M. (2016). Does training with 3D videos improve decision-making in team invasion sports? *Journal of Sports Sciences*, 34(8):746-755.

Holmes, C., Jones, R., Harland, A. & Petzing, J. (2006). Ball Launch Characteristics for Elite Rugby Union Players. In: E.F. Moritz & S. Haake (Eds), *The engineering of sport 6* (pp. 211-216). New York: Springer.

Hooper, J.J., James, S.D., Jones, D.C., Lee, D.M. & Gál, J.M. (2008). The influence of training with heavy rugby balls on selected spin pass variables in youth rugby union players. *Journal of Science and Medicine in Sport*, 11: 209-213.

Hrysomallis, C. (2011). Balance ability and athletic performance. *Sports Medicine,* 41(3): 221-232.

Hughes, M. (1988). Computerized notation analysis in field games. *Ergonomics,* 31(11): 1585-1592.

Hughes, M.D. & Bartlett R.M. (2002). The use of performance indicators in performance analysis. *Journal of Sports Sciences*, 20(10): 739-754.

Hughes, M., Caudrelier, T., James, N., Redwood-Brown, A., Donnelly, I., Kirkbride, A. & Duschesne, C. (2012). Moneyball and soccer - an analysis of the key performance indicators of elite male soccer players by position. *Journal of Human Sport & Exercise*, 7(2): 402-412.

Hughes, M.T., Hughes M.D., Williams J., James N., Vuckovic G. & Locke D. (2012). Performance indicators in rugby union. *Journal of Human Sport & Exercise*, 7(7): 383-401.

Hunter, S.K., Duchateau, J. & Enoka, R.M. (2004). Muscle fatigue and the mechanisms of task failure. *Exercise and Sport Sciences Reviews,* 32: 44-49.

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

Jackson, R.C. (2003). Pre-performance routine consistency: temporal analysis of goal kicking in the Rugby Union World Cup. *Journal of Sports Sciences*, 21: 803-814.

Jackson, R.C. & Baker, J.S. (2001). Routines, rituals, and rugby: Case study of a world class goal kicker. *Sport Psychologist,* 15: 48-65.

James, N., Mellalieu, S. & Jones, N. (2005). The development of position-specific performance indicators in professional rugby union. *Journal of Sports Sciences*, 23(1): 63-72.

Jarvis, S., Sullivan, L.O., Davies, B., Wiltshire, H. & Baker, J.S. (2009). Interrelationships between measured running intensities and agility performance in subelite rugby union players. *Research in Sports Medicine: An International Journal,* 17(4): 217-230.

Jeukendrup, A.E. (2012). Performance and endurance in sport: can it all be explained by metabolism and its manipulation? *Dialogues in Cardiovascular Medicine*, 17(1): 40-45.

Johnston, M., Cook, C.J., Crewther, B.T., Drake, D. & Kilduff, L.P. (2015). Neuromuscular, physiological and endocrine responses to a maximal speed training session in elite games players. *European Journal of Sport Science*, 15(6): 550-565.

Johnston, R.D., Gabbett, T.J., Seibold, A.J. & Jenkins, D.G. (2014). Influence of physical contact on neuromuscular fatigue and markers of muscle damage following small-sided games. *Journal of Science and Medicine in Sport,* 17: 535-540.

Johnston, R.D., Gabbett, T.J., Jenkins, D.G. & Hulin, B.T. (2015). Influence of physical qualities on post-match fatigue in rugby league players. *Journal of Science and Medicine in Sport,* 18: 209–213.

Jones, N.M.P, James, N. & Mellalieu, S.D. (2008). An objective method for depicting team performance in elite professional rugby union. *Journal of Sports Sciences*, 26(7): 691-700.

Jones, M.R., West, D.J., Harrington, B.J., Cook, C.J., Bracken, R.M., Shearer, D.A. & Kilduff, L.P. (2014). Match play performance characteristics that predict post-match creatine kinase responses in professional rugby union players. *BMC Sports Science, Medicine, and Rehabilitation*, 6(38): 1-7.

Jones, M.R., West, D.J., Crewther, B.T., Cook, C.J. & Kilduff, L.P. (2015). Quantifying positional and temporal movement patterns in professional rugby union using global positioning system. *European Journal of Sport Science*, 15(6): 488-496.

Kadaba, M.P., Ramakrishnan, H.K. & Wooten, M.E. (1990). Lower extremity kinematics during level walking. *Journal of Orthopaedic Research*, 8: 849-860.

Kallis, E. & Katis, A. (2007). Biomechanical characteristics and determinants of instep soccer kick. *Journal of Sports Science and Medicine*, 6: 154-165.

Katis, A., Giannadakis, E., Kannas, T., Amiridis, I., Kellis, E. & Lees A. (2013). Mechanisms that influence accuracy of the soccer kick. *Journal of Electromyography and Kinesiology*, 23: 125-131.

Kellis, E., Katis, A. & Vrabas, I.S. (2006). Effects of an intermittent exercise fatigue protocol on biomechanics of soccer kick performance. *Scandinavian Journal of Medicine and Science in Sports*, 16: 334-344.

Kempton, T., Kennedy, N. & Coutts, A.J. (2016). The expected value of possession in professional rugby league match-play. *Journal of Sports Sciences*, 34(7): 645-650.

Kempton, T., Sirotic, A. C., Cameron, M. & Coutts, A. J. (2013). Match-related fatigue reduces physical and technical performance during elite rugby league match-play: a case study. *Journal of Sports Sciences*, 31(16): 1770-1780.

Kempton, T., Sirotic, A.C. & Coutts, A.J. (2015). An integrated analysis of match-related fatigue in professional rugby league. *Journal of Sports Sciences*, 33(1): 39-47.

Kerr, J.H. & van Schaik, P. (1995). Effects of game venue and outcome on psychological mood states in rugby. *Personality and Individual Differences*, 19(3): 407-410.

King, N.A., Hills, A.P. & Blundell, J.E. (2005). High Body Mass Index is not a barrier to physical activity: Analysis of international rugby players' anthropometric data. *European Journal of Sport Science*, 5(2): 73-75.

Kirkpatrick, J. & Comfort, P. (2013). Strength, power, and speed qualities in English junior elite rugby league players. *Journal of Strength and Conditioning Research*, 27(9): 2414-2419.

Knicker, A.J., Renshaw, I., Oldham, A.R.H. & Cairns, S.P. (2011). Interactive processes link the multiple symptoms of fatigue in sport competition. *Sports Medicine*, 41(4): 307-328.

Kraak, W.J. & Welmen, K.E. (2014). Ruck-play as performance indicator during the (2010). Six Nations Championship. *International Journal of Sports Science & Coaching*, 9(3): 525-537.

Krustrup, P., Mohr, M., Amstrup, T., Rysgaard, T., Johansen, J., Steensberg, A., Pedersen, P. K. & Bangsbo, J. (2003). The Yo-Yo Intermittent Recovery Test: Physiological response, reliability, and validity. *Medicine & Science in Sports & Exercise*, 35(4) 697-705.

Krustrup, P., Mohr, M., Nybo, L., Majgaard Jensen, J., Jung Nielsen, J. & Bangsbo J. (2006). The Yo-Yo IR2 Test: Physiological Response, Reliability, and Application to Elite Soccer. *Medicine and Science in Sports and Exercise*, 38(9): 1666–1673.

Krustrup, P., Randers, M.B., Horton, J., Brito, J. & Rebelo, A. (2012). Ecological Validity of the Yo-Yo SFIE2 Test. *International Journal of Sports Medicine*, 33(6): 432–438.

Kyröläinen, H.,·Karinkanta, J.,·Santtila, M., Koski, H., Mäntysaari, M. & Pullinen, T. (2008). Hormonal responses during a prolonged military field exercise with variable exercise intensity. *European Journal of Applied Physiology*, 102(5): 539-546.

Lacome, M., Piscione, J., Hager, J.P. & Bourdin, M. (2014). A new approach to quantifying physical demand in rugby union. *Journal of Sports Sciences*, 32(3):290-300.

Lacome, M., Piscione, J., Hager, J.P. & Carling, C. (2015) Analysis of running and technical performance in substitute players in international male rugby union competition. *International Journal of Sports Physiology and Performance*. doi: http://dx.doi.org/10.1123/ijspp.2015-0191.

Lee, A.J., Myers, J.L. & Garraway, W.M. (1997). Influence of players' physique on rugby football injuries. *British Journal of Sports Medicine,* 31: 135-138.

Lees, A. (1999). Biomechanical assessment of individual sports for improved performance. *Sports Medicine,* 28(5): 299-305.

Lees, A. (2002). Technique analysis in sports: a critical review. *Journal of Sports Sciences*, 20(10): 813-828.

Lees, A., Asai, T., Andersen, T. B., Nunome, H. & Sterzing, T. (2010). The biomechanics of kicking in soccer: A review. *Journal of Sports Sciences*, 28: 805-817.

Lees, A. & Nolan, L. (1998). The biomechanics of soccer: a review. *Journal of Sports Sciences,* 16(3): 211-234.

Lenzi, D., Cappello, A. & Chiari, L. (2003). Influence of body segment parameters and modeling assumptions on the estimate of center of mass trajectory. *Journal of Biomechanics,* 36: 1335-1341.

Liebermann, D.G., Katz, L., Hughes, M.D., Bartlett, R.M., McClements, J. & Franks, I.M. (2002). Advances in the application of information technology to sport performance. *Journal of Sports Sciences*, 20: 755-769.

Lindsay, A., Draper, N., Lewis, J., Gieseg, S.P. & Gill, N. (2015). Positional demands of professional rugby. *European Journal of Sport Science*, 15(6): 480-487.

Linthorne, N.P. & Stokes, T.G. (2014). Optimum projection angle for attaining maximum distance in a rugby place kick. *Journal of Sports Science and Medicine*, 13: 211-216.

Lockie, R.G., Murphy, A.J., Scott, B.R. & Janse de Jonge, X.A.K. (2012). Quantifying session ratings of perceived exertion for field-based speed training methods in team sport athletes. *Journal of Strength and Conditioning Research*, 26(10): 2721-2728.

Lorenzo, A., Gómez, M.A., Ortega, E., Ibáñez, S.J. & Sampaio, J. (2010). Game related statistics which discriminate between winning and losing under-16 male basketball games. *Journal of Sports Science and Medicine*, 9: 664-668.

Lovell, D.I., Mason, D., Delphinus, E. & McLellan, C. (2013). Upper and lower body anaerobic performance of semi-elite Rugby League players. *Journal of Sports Medicine and Physical Fitness*, 53(5): 477-482.

Malik, M. & Camm, A.J. (1990). Heart rate variability. *Clinical Cardiology*, 13: 570-576.

Manolopoulos, E., Katis, A., Manolopoulos, K., Kalapotharakos, V. & Kellis, E. (2013). Effects of a 10-week resistance exercise program on soccer kick biomechanics and muscle strength. *Journal of Strength and Conditioning Research*, 27(12): 3391-3401.

Manolopoulos, E., Papadopoulos, C. & Kellis, E. (2006). Effects of combined strength and coordination training on soccer kick biomechanics in amateur players. *Scandinavian Journal of Medicine and Science in Sports*, 16: 102-110.

Martin, T.G., Pata, R.W., D'Addario, J., Yuknis, L., Kingston, R. & Feinn, R. (2015). Impact of age on haematological markers pre- and post-marathon running. *Journal of Sports Sciences*, 33(19): 1988-1997.

Mashiko, T., Umeda, T., Nakaji, S. & Sugawara, K. (2004). Position related analysis of the appearance of and relationship between post-match physical and mental fatigue in university rugby football players. *British Journal of Sports Medicine,* 38(5): 617-621.

McIntosh, A.S., McCrory, P., Finch, C.F. & Wolfe, R. (2010). Head, face and neck injury in youth rugby: incidence and risk factors. *British Journal of Sports Medicine*, 44: 188-193.

McKinon, W., Hartford, C., Di Zio, L., van Schalkwyk, J., Veliotes, D., Hofmeyr, A. & Rogers, G. (2004). The agreement between reaction-board measurements and kinematic estimation of adult male human whole body centre of mass location during running. *Physiology Measurement,* 25: 1339-1354.

McLean, D.A. (1992). Analysis of the physical demands of international rugby union. *Journal of Sports Sciences*, 10(3): 285-296.

McLean, B.D., Coutts, A.J., Kelly, V., McGuigan, M.R. & Cormack, S.J. (2010). Neuromuscular, endocrine, and perceptual fatigue responses during different length between-match microcycles in professional rugby league players. *International Journal of Sports Physiology and Performance,* 5: 367-383.

McLellan, C.P., Lovell, D.I. & Gass, G.C. (2011). The role of rate of force development on vertical jump performance. *Journal of Strength and Conditioning Research,* 25: 379-385.

McMaster, D.T., Gill, N., Cronin, J. & McGuigan, M. (2014). A brief review of strength and ballistic assessment methodologies in sport. *Sports Medicine,* 44: 603-623.

Meir, R., Holding, R. & Hetherington, J. (2014). Impact of the two-handed rugby ball carry on change of direction speed and reactive agility: implications for sport specific testing. *International Journal of Sports Science and Coaching*, 9(5): 1181-1190.

Mellalieu, S.D., Hanton, S. & O'Brien, M. (2006). The effects of goal setting on rugby performance. *Journal of Applied Behavior Analysis*, 39(2): 257-261.

Mellalieu, S.D., Hanton, S. & Thomas, O. (2009). The effects of a motivational general-arousal imagery intervention upon preperformance symptoms in male rugby union players. *Psychology of Sport and Exercise*, 10(2): 175–185.

Metaxas, T.I., Koutlianos, N.A., Kouidi, E.J. & Deligiannis A.P. (2005). Comparative study of field and laboratory tests for the evaluation of aerobic capacity in soccer players. *Journal of Strength and Conditioning Research*, 19(1): 79-84.

Milburn, P.D. (1982). Summation of segmental velocities in the golf swing. *Medicine and Science in Sports and Exercise*, 14(1): 60-64.

Milburn, P.D. The kinetics of rugby union scrummaging. (1990). *Journal of Sports Sciences*, 8: 47-60.

Milburn, P.D. (1993). Biomechanics of Rugby Union Scrummaging: Technical and safety issues. *Sports Medicine*, 16(3): 168-179.

Milburn, P.D. & Barry, E.B. (1998). Shoe-surface interaction and the reduction of injury in rugby union. *Sports Medicine*, 25: 319-327.

Moreira, A., McGuigan, M.R., Arruda, A.F.S., Freitas, C.G. & Aoki, M.S. (2012). Monitoring internal load parameters during simulated and official basketball matches. *Journal of Strength and Conditioning Research*, 26(3): 861-866.

Morel, B. & Hautier, C.A. (2016). The neuromuscular fatigue induced by repeated scrums generates instability that can be limited by appropriate recovery. *Scandinavian Journal of Medicine and Science in Sports*, 1-8. doi: 10.1111/sms.12646.

Morel, B., Rouffet, D., Bishop, D., Rota, S. & Hautier, C. (2015). Fatigue induced by repeated maximal efforts is specific to the rugby task performed. *International Journal of Sports Science & Coaching,* 10(1): 11-20.

Morris, J., Sayers, M. & Stuelcken, M. (2015) Effective lineout tactics in high performance rugby union. (Abstract). In Bangsbo, J. & Krustrup, J. (Eds). 8th World Congress on Science and Football Copenhagen, Denmark.

Mullen, T., Highton, J. & Twist, C. (2015). The internal and external responses to a forward-specific rugby league simulation protocol performed with and without physical contact. *International Journal of Sports Performance and Physiology*, 10(6): 746- 753.

Muybridge, E. (1957). Animals in Motion. Excerpted from Muybridge's 1887 Animal Locomotion. New York: Dover Publications.

Naito, K., Fukui, Y. & Maruyama, T. (2010). Multipoint kinetic chain analysis of knee extension during the soccer instep, *Human Movement Science*, 29: 259-276.

Naito, K., Fukui, Y. & Maruyama, T. (2012). Energy redistribution analysis of dynamic mechanisms of multi-body, multi-joint kinetic chain movement during soccer instep kicks. *Human Movement Science,* 31: 161–181.

Nel, J. (2013). Estimating success probability of a rugby goal kick and developing a measure for ranking rugby union goal kickers. *South African Journal for Research in Sport, Physical Education and Recreation,* 35(1): 133-142.

Nevill, A., Atkinson, G. & Hughes, M. (2008). Twenty-five years of sport performance research in the Journal of Sports Sciences. *Journal of Sports Sciences,* 26(4): 413-426.

Noakes, T.D. & du Plessis, M. (1996). Rugby without risks. (First Edition) Pretoria, South Africa. J.L. van Schaik Publishers.

Nunome, H., Ikegam, I.Y., Kozakai, R., Apriantono, T. & Sano, S. (2006). Segmental dynamics of soccer instep kicking with the preferred and non-preferred leg. *Journal of Sports Sciences,* 24(5): 529-541.

O'Donoghue, P. & Ingram, B. (2001). A notational analysis of elite tennis strategy. *Journal of Sports Sciences,* 19(2): 107-115.

Ofoghi, B., Zeleznikow, J., MacMahon, C. & Raab, M. (2013). Data Mining in Elite Sports: A Review and a Framework. *Measurement in Physical Education and Exercise Science,* 17(3): 171-186.

Olds, T. (2001). The evolution of physique in male rugby union players in the twentieth century. *Journal of Sports Sciences,* 19(4): 253-262.

Oliver, J.L., Lloyd, R.S. & Whitney, A. (2015). Monitoring of in-season neuromuscular and perceptual fatigue in youth rugby players. *European Journal of Sport Science,* 15(6): 514–522.

Ortega, E., Villarejo, D. & Palao, J.M. (2009). Differences in game statistics between winning and losing rugby teams in the Six Nations Tournament. *Journal of Sports Science and Medicine,* 8: 523-527.

O'Sullivan, S.B. (1984). Perceived Exertion: A Review. *Physical Therapy,* 64: 343-346.

Padulo, J., Granatelli, G., Ruscello, B. & D'ottavio, S. (2013). The place kick in rugby. *Journal of Sports Medicine and Physical Fitness*, 53(3): 224-231.

Paschalis, V., Giakas, G., Baltzopoulos, V., Jamurtas, A.Z., Theoharis, V., Kotzamanidis, C. & Koutedakis, Y. (2007). The effects of muscle damage following eccentric exercise on gait biomechanics. *Gait & Posture*, 25: 236-242.

Pavely, S., Adams, R.D., Di Francesco, T.I., Larkham, S. & Maher, C.G. (2009). Execution and outcome differences between passes to the left and right made by first-grade rugby union players. *Physical Therapy in Sport*, 10(4): 136-141.

Pavely, S., Adams, R.D., Di Francesco, T., Larkham, S. & Maher, C.G. (2010). Bilateral clearance punt kicking in rugby union: effects of hand used for ball delivery. *International Journal of Performance Analysis of Sport*, 10(1): 187-196.

Petersen, K., Hansen, C.B., Aagaard, P. & Madsen, K. (2007). Muscle mechanical characteristics in fatigue and recovery from a marathon race in highly trained runners. *European Journal of Applied Physiology*, 101: 385-396.

Pfeifer, C.M. (2015). *Dissertation*. Biomechanical Investigation of Elite Place-Kicking. University of Nebraska-Lincoln. http://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1095&context=mechengdiss.

Pienaar, A.E., Spamer, M.J. & Steyn Jr, H.S. (1998). Identifying and developing rugby talent among 10-year-old boys: A practical model. *Journal of Sports Sciences*, 16(8): 691-699.

Polman, R., Nicholls, A.R., Cohen, J. & Borkoles, E. (2007). The influence of game location and outcome on behaviour and mood states among professional rugby league players. *Journal of Sports Sciences*, 25(13): 1491-1500.

Posthumus, M. & Viljoen, W. (2008). BokSmart: Safe and effective techniques in rugby union. *South African Journal of Sports Medicine,* 20(3): 64-70.

Prapavessis, H. (2000). The POMS and sports performance: A review. *Journal of Applied Sport Psychology,* 12: 34-48.

Preatoni, E., Wallbaum, A., Gathercole, N., Coombes, S., Stokes, K.A. & Trewartha, G. (2012). An integrated measurement system for analysing impact biomechanics in the rugby scrum. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology,* 226: 266–273.

Preatoni, E., Stokes, K.A., England, M.E. & Trewartha, G. (2013). The influence of playing level on the biomechanical demands experienced by rugby union forwards during machine scrummaging. *Scandinavian Journal of Medicine and Science in Sports,* 23: e178-184.

Preatoni, E., Stokes, K.A., England, M.E. & Trewartha, G. (2014). Engagement techniques and playing level impact the biomechanical demands on rugby forwards during machine-based scrummaging. *British Journal of Sports Medicine,* 49(8): 520-528.

Preatoni, E., Cazzola, D., Stokes, K.A., England, M. & Trewartha, G. (2015). Pre-binding prior to full engagement improves loading conditions for front-row players in contested Rugby Union scrums. *Scandinavian Journal of Medicine and Science in Sports*, 1-10 doi:10.1111/sms.12592.

Quarrie, K.L., Handcock, P., Toomey, M.J. & Waller, A.E. (1996). The New Zealand rugby injury and physical performance comparisons performance project. IV. Anthropometric between positional categories of senior A rugby players. *British Journal of Sports Medicine*, 30: 53-56.

Quarrie, K.L. & Wilson, B.D. (2000). Force production in the rugby union scrum. *Journal of Sports Sciences,* 18(4): 237-246.

Quarrie, K.L. & Hopkins, W.G. (2007). Changes in player characteristics and match activities in Bledisloe Cup rugby union from 1972 to 2004. *Journal of Sports Sciences*, 25(8): 895-903.

Quarrie, K.L. & Hopkins, W.G. (2008). Tackle injuries in Professional Rugby Union. *American Journal of Sports Medicine,* 36:1705-1716.

Quarrie, K.L., Hopkins, W.G., Anthony, M.J. & Gill, N.D. (2013). Positional demands of international rugby union: Evaluation of player actions and movements. *Journal of Science and Medicine in Sport,* 16(4): 353-359.

Quarrie, K.L. & Hopkins, W.G. (2015). Evaluation of goal kicking performance in international rugby union matches. *Journal of Science and Medicine in Sport*, 18: 195–198.

Reilly, T. (2001). Assessment of sports performance with particular reference to field games. *European Journal of Sport Science,* 1(3): 1-12.

Robazza, C. & Bortoli, L. (2007). Perceived impact of anger and anxiety on sporting performance in rugby players. *Psychology of Sport and Exercise*, 8: 875–896.

Roberts, S.P., Trewartha, G., Higgitt, R.J., El-Abd, J. & Stokes, K.A. (2008). The physical demands of elite English rugby union. *Journal of Sports Sciences*, 26(8): 825-833

Roberts, S.P., Stokes, K.A., Weston, L. & Trewartha, G. (2010). The Bath University Rugby Shuttle Test (BURST): A Pilot Study. *International Journal of Sports Physiology and Performance*, 5(1): 64-74.

Roberts, S.P., Trewartha, G., England, M. & Stokes, K.A. (2014). Collapsed scrums and collision tackles: what is the injury risk? *British Journal of Sports Medicine,* 49(8): 536-540.

Ropret, R., Kukolj, M., Ugarkovic, D., Matavulj, D. & Jaric, S. (1998). Effects of arm loading on sprint performance. *European Journal Applied Physiology*, 77: 547-550.

Rudelsdorfer, P., Schrapf, N., Possegger, H., Mauthner, T., Bischof, H. & Tilp, M. (2014). A novel method for the analysis of sequential actions in team handball. *International Journal of Computer Science in Sport,* 13(1): 69-84.

Saboul, D., Balducci, P., Millet, G., Pialoux, V. & Hautier, C. (2016) A pilot study on quantification of training load: The use of HRV in training practice. *European Journal of Sport Science*, 16(2):172-81.

Sachlikidis, A. & Salter, C. (2007). A biomechanical comparison of dominant and non-dominant arm throws for speed and accuracy. *Sports Biomechanics*, 6: 334-344.

Saletti, D., Chicoulaa, G., Raszoudowsky, M., Drevelle, X., Piscione, J., Retière, D. & Laporte, S. (2013). Kinematic and dynamic responses of the scrum. *Computer Methods in Biomechanics and Biomedical Engineering*, 16(1): 204-205.

Saraç, M. & Zeren, F. (2013). The effect of soccer performance on stock return: Empirical evidence from “The Big Three Clubs” of Turkish soccer league. *Journal of Applied Finance & Banking,* 3(5): 299-314.

Sayers, M. (2007). Kinematic analysis of high-performance rugby props during scrum training. In T. Reilly and F. Korkusuz (Eds) Science and Football VI 46-51. New York: Routledge.

Sayers, M. & Ballon, R. (2011). Biomechanical analysis of a rugby pass from the ground. 7th World Congress of Science and Football, Nagoya, Japan 26-30 May 2011.

Sayers, M.G.L. (2011). Kinematic analysis of line-out throwing in elite international rugby union. *Journal of Sports Science and Medicine*, 10(3): 553–558.

Schache, A.G., Bennell, K.L., Blanch, P.D. & Wrigley, T.V. (1999). The coordinated movement of the lumbo–pelvic–hip complex during running: a literature review. *Gait & Posture*, 10: 30–47.

Schache, A.G., Blanch, P., Rath, D., Wrigley, T. & Bennell, K. (2002). Three-dimensional angular kinematics of the lumbar spine and pelvis during running. *Human Movement Science,* 21: 273–293.

Scott, A.C., Roe, N., Coats, A.J.S. & Piepoli, M.F. (2003). Aerobic exercise physiology in a professional rugby union team. *International Journal of Cardiology,* 87: 173–177.

Scurr, J.C., Abbott, V. & Ball, N. (2011). Quadriceps EMG muscle activation during accurate soccer instep kicking. *Journal of Sports Sciences*, 29: 247-251.

Sedeaud, A., Marc, A., Schipman, J., Taffl, M., Hager, J.P. & Toussaint, J.F (2012). How they won Rugby World Cup through height, mass and collective experience. *British Journal of Sports Medicine,* 46: 580–584.

Sedeaud, A., Marc, A., Marck, A., Dor, F., Schipman, J., Dorsey, M., Haida, A., Berthelot, G. & Toussaint, J.F. (2014). BMI, a performance parameter for speed improvement. *PLoS ONE,* 9(2): e90183. doi:10.1371/journal.pone.0090183.

Seo, K., Kobayashi, O. & Murakami, M. (2006). Flight dynamics of the screw kick in rugby. *Sports Engineering*, 9(1): 49-58.

Shan, G. & Westerhoff, P. (2005). Full body kinematics characteristics of the maximal instep soccer kick by male soccer players and parameters related to kick quality. *Sports Biomechanics*, 4(1): 59-72.

Sharp, T., Halaki, M., Greene, A. & Vanwanseele, B. (2014). An EMG assessment of front row rugby union scrummaging. *International Journal of Performance Analysis in Sport*, 14: 225-237.

Shaw, A.J., Ingham, S.A., Atkinson, G. & Folland, J.P. (2015). The correlation between running economy and maximal oxygen uptake: cross- sectional and longitudinal relationships in highly trained distance runners. *PLoS ONE,* 10(4): e0123101. doi:10.1371/journal.pone.0123101.

Sinclair, J., Taylor, J.P., Atkins, S. & Hobbs, S.J. (2013). Upper body kinematic predictors of ball velocity during out of hand kicking in international level rugby league kickers. *International Journal of Sports Science and Engineering*, 7(2):101-110.

Sinclair, J., Taylor, P. J., Atkins, S., Bullen, J., Smith, A. & Hobbs, S. J. (2014a). The influence of lower extremity kinematics on ball release velocity during instep place kicking in rugby union. *International Journal of Performance Analysis in Sport*, 14(1): 64-72.

Sinclair, J., Fewtrell, D., Taylor, P.J., Bottoms, L., Atkins, S. & Hobbs, S.J. (2014b). Three-dimensional kinematic correlates of ball velocity during maximal instep soccer kicking in males. *European Journal of Sport Science*, 14(8): 799-805.

Sinnett, A.M., Berg, K., Latin, R.W. & Noble, J.M. (2001). The relationship between field tests of anaerobic power and 10-km run performance. *Journal of Strength and Conditioning Research,* 15(4): 405-12.

Sirotic, A.C. & Coutts, A.J. (2007). physiological and performance test correlates of prolonged, high-intensity, intermittent running performance in moderately trained women team sport athletes. *Journal of Strength and Conditioning Research*, 21(1): 138–144.

Smart, D.J., Gill, N.D., Beaven, C.M., Cook, C.J. & Blazevich, A.J. (2008). The relationship between changes in interstitial creatine kinase and game-related impacts in rugby union. *British Journal of Sports Medicine*, 42(3), 198-201.

Smart, D.J., Hopkins, W.G., & Gill, N.D. (2013). Differences and changes in the physical characteristics of professional and amateur rugby union players. *Journal of Strength and Conditioning Research,* 27(11): 3033–3044.

Spamer, E.J., du Plessis, D.J. & Kruger, E.H. (2009). Comparative characteristics of elite New Zealand and South African u/16 rugby players with reference to game specific skills, physical abilities and anthropometric data. *South African Journal of Sports Medicine,* 21(2): 53-57.

Speranza, M.J.A., Gabbett, T.J., Johnston, R.D. & Sheppard, J.M. (2016). Effect of strength and power training on tackling ability in semiprofessional rugby league players. *Journal of Strength and Conditioning Research,* 30(2): 336–343.

St Clair Gibson, A., Baden, D.A., Lambert, M.I. Lambert, E.V., Harley, Y.X.R., Hampson, D., Russell, V.A. & Noakes, T.D. (2003). The conscious perception of the sensation of fatigue. *Sports Medicine*; 33(3): 167-176.

Stanula, A. & Roczniok, R. (2013). Relations between BMI, body mass and height, and sports competence among participants of the 2010 winter Olympic games: does sport metabolic demand differentiate? *Perceptual & Motor Skills: Motor Skills & Ergonomics,* 117(3): 837-854.

Stirling, L.M., Von Tscharner, V., Fletcher, J.R. & Nigg, B.M. (2012). Quantification of the manifestations of fatigue during treadmill running. *European Journal of Sport Science* 12, 418-424.

Stone, K.J., Hughes, M.G., Stembridge, M.R., Meyers, R.W., Newcombe, D.J. & Oliver, J.L. (2016). The influence of playing surface on physiological and performance responses during and after soccer simulation. *European Journal of Sport Science,* 16(1): 42-49.

Stoszkowski, J. & Collins, D. (2016). Sources, topics and use of knowledge by coaches. *Journal of Sports Sciences*, 34(9):794-802.

Stuart, G.R., Hopkins, W.G., Cook, C. & Cairns, S.P. (2005). Multiple effects of caffeine on simulated high-intensity team-sport performance. *Medicine & Science in Sports & Exercise*, 37(11): 1998–2005.

Swaminathan, R., Williams, J.M., Jones, M.D. & Theobald, P.S. (2016). A kinematic analysis of the spine during rugby scrummaging on natural and synthetic turfs. *Journal of Sports Sciences*, 34(11): 1058-1066.

Takarada, Y. (2003). Evaluation of muscle damage after a rugby match with special reference to tackle plays. *British Journal of Sports Medicine*, 37(5): 416–419.

Taylor, T., West, D.J., Howatson, G., Jones, C., Bracken, R.M., Love, T.D., Cook, C.J., Swift, E., Baker, J.S. & Kilduff, L.P. (2015). The impact of neuromuscular electrical stimulation on recovery after intensive, muscle damaging, maximal speed training in professional team sports players. *Journal of Science and Medicine in Sport;* 18: 328–332

Teixeira, L.A. (1999). Kinematics of kicking as a function of different sources of constraint on accuracy. *Perceptual and Motor Skills,* 88: 785-789.

Terry, P.C., Walrond, N. & Carron, A.V. (1998). The influence of game location on athletes' psychological states. *Journal of Science and Medicine in Sport*, 1(1): 29-37

Till, K., Tester, E., Jones, B., Emmonds, S., Fahey, J. & Cooke, C. (2014). Anthropometric and physical characteristics of English academy rugby league players. *Journal of Strength and Conditioning Research*, 28(2): 319–327.

Tomlinson, S. E., Lewis, R., Ball, S., Yoxall, A. & Carre, M. J. (2009). Understanding the effect of finger–ball friction on the handling performance of rugby balls. *Sports Engineering*, 11:109–118.

Tønnessen, E., Haugen, T.A., Hem, E., Leirstein, S. & Seiler, S. (2015). Maximal aerobic capacity in the Winter-Olympics endurance disciplines: Olympic-medal benchmarks for the time period 1990–2013. *International Journal of Sports Physiology and Performance*, 10: 835 -839.

Totterdell, P. (2000). Catching moods and hitting runs: mood linkage and subjective performance in professional sport teams. *Journal of Applied Psychology*, 85(6): 848-859.

Travassos, B., Davids, K., Araújo, D. & Esteves, P.T. (2013). Performance analysis in team sports: advances from an ecological dynamics approach. *International Journal of Performance Analysis in Sport*, 13: 83-95.

Trewartha, G., Casanova, R. & Wilson, C. (2008). A kinematic analysis of rugby lineout throwing. *Journal of Sports Sciences*, 26(8): 845-854.

Tsatalas, T., Giakas, G., Spyropoulos, G., Paschalis, V., Nikolaidis, M.G., Tsaopoulos, D.E., Theodorou, A.A., Jamurtas, A.Z. & Koutedakis, Y. (2010). The effects of muscle damage on walking biomechanics are speed-dependent. *European Journal of Applied Physiology*, 110: 977–988.

Twist, C., Waldron, M., Highton, J., Burt, D. & Daniels, M. (2012). Neuromuscular, biochemical and perceptual post-match fatigue in professional rugby league forwards and backs. *Journal of Sports Sciences*, 30(4): 359–367.

Urbin, M.A., Stodden, D.F., Fischman, M.G., & Weimar, W.H. (2011). Impulse-Variability Theory: Implications for ballistics multijoint motor skill performance. *Journal of Motor Behavior*, 43: 275-283.

Vaz, L., Van Rooyen, M. & Sampaio, J. (2010). Rugby game-related statistics that discriminate between winning and losing teams in IRB and Super twelve close games. *Journal of Sports Science and Medicine*, 9: 51-55.

Walsh, M., Young, B., Hill, B., Kittredge, K. & Horn, T. (2007). The effect of ball-carrying technique and experience on sprinting in rugby union. *Journal of Sports Sciences*, 25(2): 185-192.

Watts, A.S., Coleman, I. & Nevill, A. (2012). The changing shape characteristics associated with success in world-class sprinters. *Journal of Sports Sciences*, 30(11): 1085-1095.

Weiner, I.D., Mitch, W.E. & Sands, J.M. (2015). Urea and ammonia metabolism and the control of renal nitrogen excretion. *Clinical Journal of the American Society of Nephrology*, 10: 1444–1458.

Weippert, M., Kumar, M., Kreuzfeld, S., Arndt, D., Rieger, A. & Stoll, R. (2010). Comparison of three mobile devices for measuring R–R intervals and heart rate variability: Polar S810i, Suunto t6 and an ambulatory ECG system. *European Journal of Applied Physiology*, 109(4): 779-786.

Weir, J.P., Beck, T.W., Cramer, J.T. & Housh, T.J. (2006). Is fatigue all in your head? A critical review of the central governor model. *British Journal of Sports Medicine,* 40: 573-586.

West, D.J., Finn, C.V., Cunningham, D.J., Shearer, D.A., Jones, M.R., Harrington, B.J., Crewther, B.T., Cook, C.J. & Kilduff, L.P. (2014). Neuromuscular function, hormonal, and mood responses to a professional rugby union match. *Journal of Strength and Conditioning Research*, 28(1): 194–200.

Westerblad, H., Allen, D.G. & Lännergren, J. (2002). Muscle fatigue: lactic acid or inorganic phosphate the major cause? *News in Physiological Science*, 17: 17-21.

Wetzler, M.J., Akpata, T., Laughlin, W. & Levy, A.S. (1998). Occurrence of cervical spine injuries during the rugby scrum. *American Journal of Sports Medicine,* 26(2):177-180.

Wheeler, K.W. & Sayers, M.G. (2010). Modification of agility running technique in reaction to a defender in rugby union. *Journal of Sports Science and Medicine*, 9(3): 445-451.

Wiewelhove, T., Raeder, C., Meyer, T., Kellmann, M., Pfeiffer, M. & Ferrauti, A. (2015). Markers for routine assessment of fatigue and recovery in male and female team sport athletes during high-intensity interval training. *PLoS ONE,* 10(10):1-17.

Williams, S., Trewartha, G., Kemp, S.P.T, Brooks, J.H.M., Fuller, C.W., Taylor, A.E., Cross, M.J. & Stokes K.A. (2015). Time loss injuries compromise team success in Elite Rugby Union: a 7-year prospective study. *British Journal of Sports Medicine,* 1–6. doi:10.1136/bjsports-2015-094798.

Williams, J.D., Abt, G. & Kilding, A.E. (2010). Ball-sport endurance and sprint test (BEAST90): validity and reliability of a 90-minute soccer performance test. *Journal of Strength & Conditioning Research*, 24(12): 3209-3218.

World Rugby Laws of the Game. http://laws.worldrugby.org/index.php?law=20&language=EN. Accessed 1 March 2015

World Rugby Law Trials http://www.worldrugby.org/news/90108. Accessed 20 December 2015.

World Rugby website. http://www.worldrugby.org/development/player-numbers. Accessed 1 December 2015.

Worsfold, P.R. & Page, M. (2014). The influences of rugby spin pass technique on movement time, ball velocity and passing accuracy. *International Journal of Performance Analysis in Sport,* 14(1): 296-306.

Wu, W.L., Chang, J.J., Wu, J.H. & Guo, L.Y. (2007). An investigation of rugby scrummaging posture and individual maximum pushing force. *Journal of Strength and Conditioning Research,* 21: 251–258.

Zago, M., Motta, A.F., Mapelli, A., Annoni, I., Galvani, C. & Sforza, C. (2014). Effect of leg dominance on the center-of-mass kinematics during an inside-of-the-foot kick in amateur soccer players *Journal of Human Kinetics,* 42: 51-61.

Zago, M., Piovan, A.G., Annoni, I., Ciprandi, D., Iaia, F.M. & Sforza, C. (2016). Dribbling determinants in sub-elite youth soccer players. *Journal of Sports Sciences*. 34(5):411-419.

Zhang, Y., Liu, G. & Xie, S. (2012). Movement sequences during instep rugby kick: a 3D biomechanical analysis. *International Journal of Sports Science and Engineering*, 6(2), 89-95.

Appendices

Appendix 1: Defining the playing positions in Rugby

The fifteen players on a rugby team are classified in different positional groups depending on their anthropometry, skills and gameplay. The two major classes are the forwards and the backs. The eight forwards consist:

- The two props, a loose-head and tight-head (player numbers 1 and 3) are responsible for scrummaging tasks and lifting players in the line-outs.
- A hooker (2) will bind between the two props to make up the front row of the scrum. A hooker will be responsible for throwing in the ball during a line-out.
- The final additions to the tight five (tight forwards) are the two locks (numbers 4 and 5). The locks will bind onto the front row of the scrum, and have been described as the 'engine' of the scrum. Locks are normally the players that are lifted during the line-out making them the target of the intended throw-in.

The tight forwards are largely involved in the intense static competitions such as scrums and mauls.

- Flankers (blind-side and open-side numbers 6 and 7) are seen as all rounded rugby players. In the scrum they will assist their props and may jump or lift in the line-outs. Flankers will contest for possession of the ball through tackles, rucks and mauls.
- The number eight (8) is the main link between the forwards and the backs, specifically at the scrum. The number eight, together with the flankers comprise the loose forwards.

The loose forwards will generally make the most tackles, be tackled more often and make the most number of high intensity runs of the forwards (Lindsay et al., 2015).

The seven players that constitute the backs are:

- The scrum-half (9) is usually the main link between the backs and the forwards, as they will receiver that ball from the line-out, scrum or gather the ball from the base of a ruck. This position requires a player to effectively keep up with the speed of the game and accurately distribute the ball to the remaining backline players.
- The position of fly-half (10) is arguably the most important position of the team. The fly-half is the determining factor as to how the team will play, as they decide whether the ball should be kicked or passed. The kicks for goals are usually performed by the fly-half.
- The two centres (inside, number 12, and outside, number 13) are usual the main defenders in the backline. Their attacking roles require them to possess the skill to create and identify space for the team to exploit and attack.
- The two wings (number 11 left wing, and 14, right wing) are the speed players, that will usually score the tries through outright pace. Although the wings along with the fullback are important in defence as they are normally the last players that could potential stop the opponents from scoring tries.
- The fullback (15) is the last player in the defensive line. Their play usually involves sweeping defensive lines and kicking out of hand for territory. The fullbacks along with the fly-halves are normally those that attempt to kick for posts.

The definitions of the playing positions were derived from Noakes and du Plessis (1996) and from freely available sources, namely the World Rugby Training Passport https://passport.worldrugby.org/?page=beginners&p=10&t=15 and Trueman http://www.rugbyfootballhistory.com/positions.html

Appendix 2: Ethical clearance certificate

HUMAN RESEARCH ETHICS COMMITTEE (MEDICAL)

CLEARANCE CERTIFICATE NO. M131019

NAME: (Principal Investigator)	Mr Andrew Green et al
DEPARTMENT:	School of Physiology Medical School
PROJECT TITLE:	The Physiological and Biomechanical Responses to Muscle Fatigue from Non-Specific and Rugby Specific Tasks
DATE CONSIDERED:	25/10/2013
DECISION:	Approved unconditionally
CONDITIONS:	
SUPERVISOR:	Dr Warrick McKinon
APPROVED BY:	Professor PE Cleaton-Jones, Chairperson, HREC (Medical)

DATE OF APPROVAL: 22/11/2013

This clearance certificate is valid for 5 years from date of approval. Extension may be applied for.

DECLARATION OF INVESTIGATORS

To be completed in duplicate and **ONE COPY** returned to the Secretary in Room 10004, 10th floor, Senate House, University.

I/we fully understand the conditions under which I am/we are authorized to carry out the above-mentioned research and I/we undertake to ensure compliance with these conditions. Should any departure be contemplated, from the research protocol as approved, I/we undertake to resubmit the application to the Committee. **I agree to submit a yearly progress report**

Principal Investigator Signature M131019Date

PLEASE QUOTE THE PROTOCOL NUMBER IN ALL ENQUIRIES

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24 March 2016

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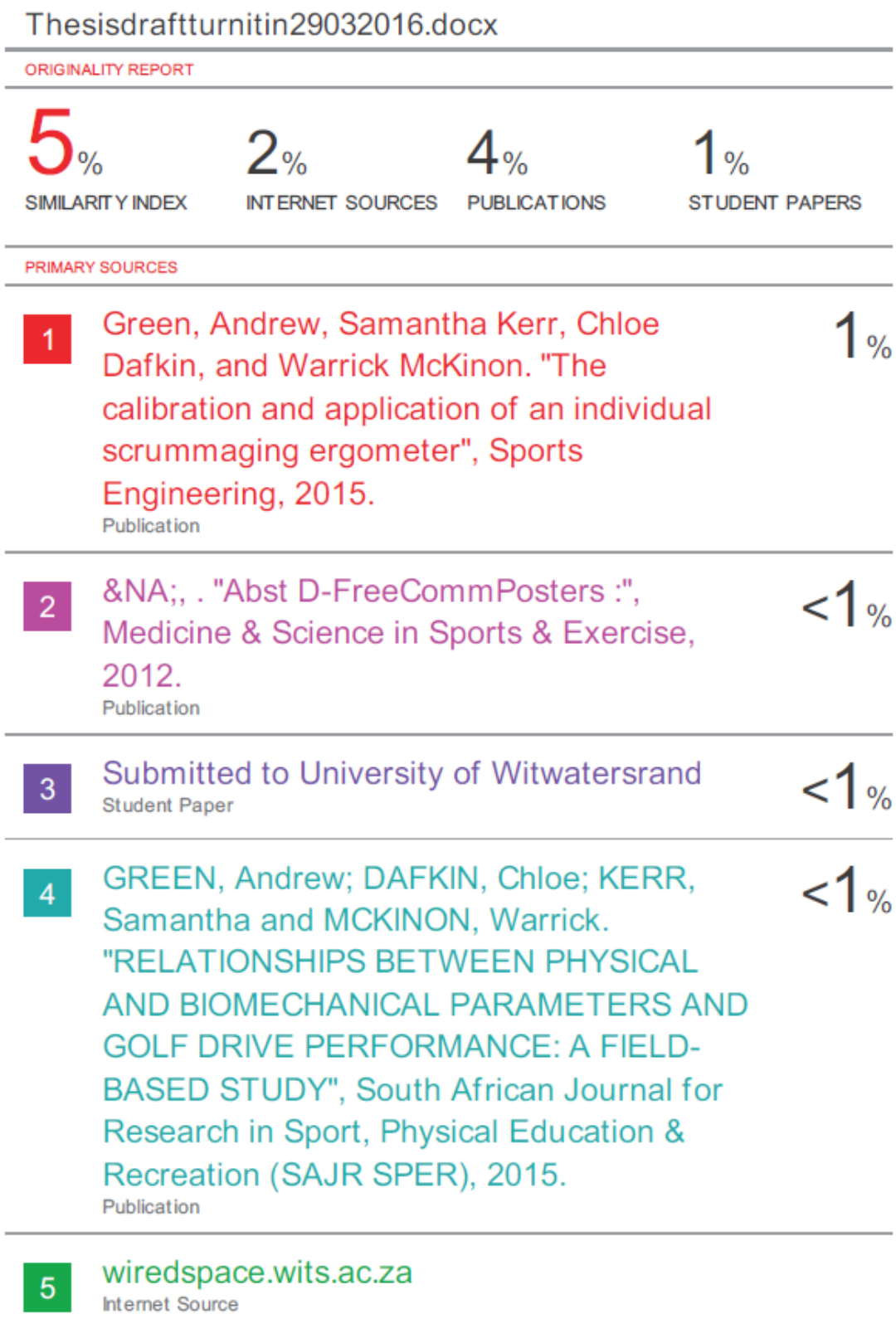
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