Biomechanical Analysis of the Rugby Place Kick

by
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Thesis presented in fulfilment of the requirements for the degree of
Master of Engineering (Mechatronic) in the Faculty of
Engineering at Stellenbosch University

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March 2018

DECLARATION

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ABSTRACT

Compared to other professional sport codes such as soccer, the availability of rugby-based studies rooted in scientific principles is limited. This study forms part of a larger project that aims to broaden the knowledge base surrounding the rugby goal kick.

This study set out to achieve the following three objectives: to determine the ideal frequency parameters for the use on kinematic variables during the analysis of the rugby goal kick, testing the validity of possible automatic filtering algorithms applied to the kinematic variables and the identification of a concrete kinematic sequence performed during the rugby goal kicks, by implementing biomechanical analysis principles.

In order to achieve this, the three-dimensional kinematic data of twelve elite level kickers were recorded using an 8- camera Vicon system sampling at frequencies of 200 Hz. The testing was conducted at the motion-analysis laboratory at the University of Stellenbosch. The participants were all of national calibre at the time of testing. Each participant performed ten consecutive goal kicks. The testing was conducted on hard rubber floors with the participants wearing running shoes.

The effect of the filtering process was visually observed in order to determine the ideal filtering parameters for the kinematic variables. Based on these findings, the validity of several automatic filtering algorithms was tested.

It was established that none of the automatic filtering algorithms tested during the study achieved satisfactory results for the use with rugby goal kick kinematic data.

The study, however, successfully identified an ideal filtering frequency that could be applied to biomechanical data of such a nature as a rugby goal kick. It furthermore established a kinematic sequence that is performed during the execution of a rugby goal kick.

OPSOMMING

In vergelyking met ander professionele sportkodes soos sokker, is daar beperkte beskikbaarheid van wetenskaplik gebasseerde studies rakende rugby. Hierdie studie vorm deel van 'n groter projek wat daarop gemik is om die kennisbasis rondom die rugby stelskop te verbreed.

Die studie het dit ten doel om die volgende drie doelwitte te bereik: om die ideale frekwensie parameters vir gebruik met kinematiese veranderlikes gedurende die analise van die rugby stelskop te bepaal, om die geldigheid van moontlike outomatiese filtrering algoritmes wat toegepas word op die kinematiese veranderlikes te bepaal, en om 'n vasgestelde kinematiese reeks te bepaal wat tydens die rugby stelskop uitgevoer word, deur die implementering van biomeganiese beginsels.

Om die bogenoemde doelwitte te bereik is drie-dimensionele kinematiese data versamel van twaalf professionele rugby stelskoppers. Die data is versamel deur 'n 8-kamera Vicon sisteem te gebruik wat teen 'n frekwensie van 200 Hz opneem. Die toetse is uitgevoer in die bewegingslaboratorium van Universiteit van Stelllenbosch. Die deelnemers hat almal op nasionale vlak aan rugby deelgeneem tydens die tydperk waartydens die data versamel is. Elke deelnemer het tien agtereenvolgende stelskoppe uitgevoer. Die toetse is binnenshuis afgeneem. Die laboratorium het 'n harde rubber vloeroppervvlak en die deelnemers het die skoppe uitgevoer met hardloopskoene.

Die invloed van die filtreringsproses op die kinematiese data is visueel waargeneem met die doel om die ideale filtreringsparameters vir kinematiese veranderlikes te bepaal. Na aanleiding van die boegnoemde resultate is daar tot die volgende gevolgtekking gekom: die outomatiese filtreringsalgoritmes wat in hierdie studie getoets is het nie bevredigende resultate vir die kinematiese data van 'n stelskop gelewer nie.

Die studie het egter wel 'n ideale filtreringsfrekwensie bepaal vir die toepassing op rugby stelskop kinematiese data. Hierdie filtreringsfrekwensie het my in staat gestel om 'n kinmatiese reeks vir die rugby stelskop te identifiseer.

ACKNOWLEDGEMENTS

I would like to express my sincere appreciation to my Principle Supervisor, Dr D Van den Heever and Co-supervisor, Dr J Cockcroft for their constant guidance and encouragement, without which this work would not have been possible. For their unwavering support, I am truly grateful.

To my family, especially to my mother and farther for the unwavering emotional support throughout the project. The lessons you have taught me throughout my life has brought me to this point. Without your support and guidance, I would not have been able to complete the project.

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INTRODUCTION

1.1 INTRODUCTION

Rugby union has continuously grown since the first professional match was played in 1967. It started out as a simple pass-time but has been transformed into a global attraction with vast stadia, an intricate administrative structure and complex strategies. It is enjoyed as the national sport for several countries from a wide range of socio-economic backgrounds. South Africa has consistently been one of the top tier rugby nations in the world, only occasionally dropping out of the top 4 in the international rankings.

According to the International Rugby Board (IRB) there are currently 2.82 million registered rugby union players in the world; this number grew from 2.56 million in the year 2015.The number of non-registered rugby players rose from 4.47 million to 4.91 million in the same time period. The IRB contributes this to a record amount of funding through the World Rugby Development Programme (£8.23 m), Regional Tournament Funding (£3.82 m) and High Performance Programme (£10.68 m). Since the year 2015 a record number of 120 countries now belong to unions affiliated with the IRB (World Rugby, 2015b).

Even the increased growth rugby has experienced in recent history; it is dwarfed by the sheer scale of support enjoyed by soccer. During the previous survey conducted by FIFA in 2006 it was estimated that there are more than 38 million registered soccer players around the world and that approximately 4% of the world's population plays the sport recreationally (Fédération Internationale de Football Association (FIFA), 2007). The difference in scale between rugby and soccer is made evident by the difference in the ten highest earning players of each sport for the year of 2017, as shown in Table 1 (Forbes, 2017) (Tewhatu, 2017).

Even though the sport continues to grow on both the domestic and international level, coupled with an increasing player base and funding, scientific based research of rugby is limited. This is especially true when referring to the biomechanics of rugby goal kicking. This study aims to broaden the body of knowledge connecting to rugby goal kicking, by means of a biomechanical analysis.

Table 1: Comparison between the highest earnings per season in million between soccer and rugby

	Rugby (million)	Soccer (million)
1	$1.98	$93
2	$1.98	$80
3	$1.28	$37
4	$0.95	$34
5	$0.71	$32
6	$0.71	$23.6
7	$0.71	$23.3
8	$0.71	$22.6
9	$0.68	$21.9
10	$0.64	$21.2

This study forms part of a larger project that aims to acquire scientific knowledge concerning the biomechanics of the rugby goal kick. The project will span across multiple phases and disciplines. The knowledge acquired will serve as a base to establish a youth development program that aims to bring the level of South African players and coaches to that of the world’s best. In order to develop such a program, the scientific body of knowledge surrounding the game of rugby must be expanded. By understanding the fundamental aspects of the rugby goal kick movement, coaches will be able to improve the fundamental skills of young players, which will greatly improve the performance of players on higher levels of competition.

This study aims to broaden the body of knowledge surrounding the rugby goal kick. By furthering the understanding of the fundamental aspects of this movement, coaches and trainers will be able to implement training protocols based on scientific data on rugby goal kicking, instead of altering findings from soccer studies. This will result in a decrease in the subjectivity traditionally associated with coach and trainer feedback to athletes. The improved training and coaching protocols could lead to improved performance of kickers across all sporting levels.

1.2 CONTEXT OF THE STUDY

South Africa annually competes in national level (Rugby Championship) and provincial level (Super Rugby) tournaments with its biggest rivals, New Zealand and Australia. According to the statistics released by IRB in 2014, South Africa has more than double the number of registered players compared to New Zealand and about 1.5 times the number of players of Australia (World Rugby, 2015b). Even with such a large advantage in player base, South Africa has only managed to win 14 of their 33 matches since the inclusion of Argentina in 2012 (ESPN Scrum, 2017).

The rugby place kick is an important and fundamental aspect in the game of rugby. Throughout the history of the sport, many matches and trophies were either won or lost by the boot of a kicker. In a study analysing 582 international matches played between

2002 and 2011, it was found that 72% of the 6769 kicking attempts were successful, constituting 45% of the total points scored during this period. The outcome of 33 of the matches played hinged on the success of a goal kick (Quarrie & Hopkins, 2014). During the six Rugby World Cup (RWC) finals before 2015, the finalists produced only seven tries, while having produced a total of 37 penalty goals. This results in a ratio of one try to five penalty goals with six of the twelve finalists failing to score even a single try and only a single team managing to score more than one try (World Rugby, 2015a). During the history of the RWC a cumulative total of 259 points have been scored in finals, 31% of which are attributed to tries scored, 8% to conversions and 54% due to penalty kicks.

Many believe the lack of positive results is due to lacking the same level of skill as some of their competition (Cardinelli, 2015) (Mohamed, 2016). It is believed that the greater focus on developing the required skillset, more so than the physical aspects, of young players is the key to the success of nations such as New Zealand and Australia. The implementation of a dedicated youth development program by South Africa may serve to bridge the gap. In order for South Africa to develop such a program, a great deal of time must be invested to further the knowledge base of coaching and training by not focussing on immediate performance only (The Sport Freak, 2016). Coaches and trainers must become knowledgeable about more than just what the “final” or “ideal” technique of an elite level athlete looks like. They must focus on more than just the physicality of a young player and tailor the player’s skills according to their personal “technique” and strengths.

A bibliometric study using the keyword “Rugby” was conducted on journal articles in scientific journals published between 1922 and 2009. The search was conducted on three databases: Scopus, ISI Web of Knowledge and Sports Discus. Of the 2057 articles analysed, only 45 (2.2%) focussed on the biomechanics of a rugby related movement (Martin, Olmo, Chirosa, Carreras, & Sola, 2013). Of these, studies’ pertaining to kicking movement’s make up only a small portion. This highlights the dire need for additional scientific based studies based on such a vital aspect of the game of rugby.

1.3 PROBLEM STATEMENT

Even with the large player base around the world and a great deal of funding going towards rugby development, the scientific study of rugby is limited, especially in terms of biomechanics. Currently there is only a small biomechanics community dedicated to the analysis of the rugby union movements, with goal kicking being only one of the many movements in rugby union as a whole. The studies that do indeed focus on the investigation of the goal kick are usually limited to only a selected aspect of the movement, failing to address the movement as a whole, such as obtaining the optimum elevation angle for maximum kicking distance or focussing only on the foot speed (Simons, 2016) (Linthorne & Stokes, Optimum projection angle for attaining maximum distance in a rugby place kick., 2014). Given the resemblance between the rugby union goal kick and the free kick in soccer or football (referred to as soccer from this point onwards) and soccer being a more global sport, most studies concerning the rugby union goal kick reference soccer studies (Atack, Trewartha, & Bezodis, 2014) (Bezodis, Trewartha, Wilson, & Irwin, 2007). However, according to a study examining the biomechanics of the kicking leg during a rugby goal kick, it was found that although the two movements are indeed similar, there are some mechanical differences between a rugby goal kick and a free kick in soccer (Atack, et al., 2014). Based on the findings of Atack et al (2014) there exists a need to further grow the scientific knowledge base surrounding the game of rugby, and the reliance on studies related to the soccer disciple must be reduced.

Coupled with the lack of dedicated rugby goal kicking studies, is the lack of research based on the around the filtering and processing of rugby biomechanical data. There furthermore does not seem to be a consensus on the filtering parameters used for the kinematic data. The cut-off frequencies that have been reported vary from study to study and are usually based on visual inspection only. This is however not a feasible practise as it is susceptible to human judgement and can be a time consuming endeavour when multiple signals need to be processed, as is the case with rugby goal kicking study.

1.4 AIM

The current phase of the project (this study) has a two-fold aim. Firstly, the study aims to implement several automatic filtering algorithms and investigate their effect on the validity of the filtered data. Secondly, the study aims to develop a tool for the analysis of kinematic data generated from the three-dimensional motion capturing of a rugby goal kick. Emphasis is placed on the extraction of the kinematic sequence as well as implementing the most suitable filtering protocol established. The kinematic sequence reveals the segmental interaction during the movement. This involves determining the order of joint interaction/movements, i.e. the pattern or timing at which certain key movements are executed. The kinematic sequence, along with the magnitude of the segment velocities, will allow the further study of the different kicking styles exhibited by certain goal kickers. The processing techniques developed during this study will serve as a base for the subsequent phases in the larger project.

1.5 OBJECTIVES

The following research objectives were formulated, namely to:

- Determine suitable filtering frequencies for the use on joint kinematics during the rugby goal kick.

Due to the nature of the frequency content of a non-periodical movement that involves influences from external sources such as kicking a ball, the standard recommendations and procedures outlined for filtering movements such as gait do not fully satisfy the filtering requirements of a rugby goal kick. Therefore, the ideal filtering parameters specifically applicable to the rugby goal kick must be determined.

- Implement and test the validity of several automatic filtering algorithms in order to establish a suitable filtering protocol for rugby goal kick kinematics.

Determining the filtering frequencies by means of visual inspection is not suitable to a multi-join full body movement such as a rugby goal kick. Therefore, some means of automating this process is required.

- Develop a tool to process the kinematic data of a rugby goal kick, by extracting the kinematic sequence.

In order to further understand the fundamental aspects of the rugby goal kick, it is required to analyse the interaction between the segments that contribute the generation of foot speed and orientation.

1.6 SIGNIFICANCE OF THE STUDY

The implementation of an automatic filtering algorithm will greatly ease the process of analysing multi-segment whole body movements such as the rugby goal kick. It would remove the need for constantly scrutinising the filtering process. However, in order to test the validity of the results found by one of these algorithms, the frequency content of rugby goal kicking kinematics must be known. This study will aim to determine the ideal filtering parameter that could be applied to rugby goal kicking kinematics.

The broader goal of the study is to deepen the scientific pool of knowledge surrounding the rugby goal kicking movement. Only through scientific based empirical data will the coaching be elevated to the same level as that of the larger global sports. The findings of this study will serve as a base on which the larger project can be furthered.

1.7 PROPOSED LAYOUT OF THE STUDY

The review of the literature in Chapter two highlights the skill acquisition process and the importance of building a knowledge base around the rugby goal kicking movement. This discussion is followed by a discussion on the biomechanics tools and techniques utilised in the processing and analysis of three-dimensional biomechanical data. Chapter two is concluded with a discussion on the automatic filtering algorithms being tested in this study.

Chapter three presents the methodology used to collect process and analyse the biomechanical data needed to fulfil the aim of the study. In Chapter four the results of the most appropriate filtering technique for the biomechanical data of a rugby goal kick are presented and discussed, followed by the results and discussion on the biomechanical analysis of the data set of the twelve participants. The chapter is concluded with the identification of a possible kinematic sequence. The study is concluded in Chapter 5. The limitation of the study is discussed, followed by recommendations for future research.

CHAPTER TWO

LITERATURE REVIEW

2.1 INTRODUCTION

Throughout this report the key elements of a rugby union goal kick as well as the effect it has on the successful performance of the movement will be analysed. In this literature study, the importance of furthering the understanding of the rugby place kicking technique for both the improvement of the sport as well as furthering the biomechanical body of knowledge will be discussed. Concepts, such as what the study of biomechanics entail and why furthering the body of knowledge is important, the different analysis methods and techniques used in biomechanics, etc. will be discussed. Next, the motion capturing techniques, two-dimensional vs. three-dimensional, and the biomechanical research done on both the rugby union place kick and the in-step kick implemented in soccer will be outlined. Finally, the reference measures, necessary to statistically explore the relationship between the execution and the performance outcome, will be defined.

2.2 SKILL ACQUSITION

The acquisition of perceptual-motor skills is fundamental to human development. Humans continuously strive to either acquire new skills or refine existing ones. Skilled athletes spend many hours practicing and honing their skills with the aim of improving their performance (Hodges & Williams, 2012) (Williams & Hodges, 2005). However, without fully understanding the fundamental aspects of the movement and having the knowledge to determine the best use of time and resources, athletes will be unable to reach their full potential. This project strives to understand the skill associated with the rugby goal kick and how it is acquired using scientific based methods.

There is a large debate within sport science about whether champions are either born or bred (Baker & Davids, 2006) (Tucker & Collins, 2012) (Helsen, Hodges, Van Winckel, & Starkes, 2000). Research has concluded that it takes 10,000 hours of training for a talented player/athlete to reach elite level. This translates to approximately three hours daily practice for ten years (Hodges & Williams, 2012) (Williams & Hodges, 2005). Many warn against taking this concept too literally, but there is general consensus that it is not possible to reach expert-level performance without a long term commitment to training and practice (Howe, Davids , & Sloboda, 1998) (Scurr & Hall, 2009) (Balyi & Hamilton, 2004) (Tucker, 2013) (Ward, Hodges, Starkes, & Williams, 2007). Training alone, however, does not equate to skill. Athletes are required to engage in deliberate practice, defined as highly effortful and structured activity with the explicit goal of improving performance through participating in specific activities focussing on improving weaknesses (Baker & Young, 2014) (Hodges & Williams, 2012) (Ericsson, 2004).

The long-term training of athletes and players can be separated into several stages that progress as the athlete or player matures. Early stages start with obtaining the fundamental skills required in sports, such as the physical strength and control required to perform the required motions. From the early stages, the athlete can start to learn the basic structure of the movement and as the athlete becomes more proficient, the focus of training shifts more towards performance outcome (Balyi & Hamilton, 2004) (Côté & Vierimaa, 2014) (Hendriks, 2012). At this stage the coach and trainer must assist the player in identifying the inherent dynamics of the individual, opposed to trying to reproduce “expert behaviour”. Focusing on the “ideal” movement could lead to frustration and even prolong the skill acquisition process (Seifert, Button, & Davids , 2013) (Ackland, Elliott, & Bloomfield, 2009). In order for a trainer or coach to help develop a personalised style for an athlete, the fundamental aspects of that movement must be known. Attempting to duplicate a movement without understanding the cause and effects could result in sub optimal movement patterns. If the changes made to the movement are based on expert knowledge and fundamental principles, the true potential of an athlete can be unlocked.

Elite level athletes on the other hand already possess a unique technique that has been ingrained after an extended period of training. Attempting to drastically alter their technique could lead to regression in their performance (Carson & Collins, 2014). Therefore, in the case of elite athletes, their skill should subtly be refined by either decreasing variability or utilizing a more personalised training program focussing on individual weak areas (Bartlett, Wheat, & Robins, 2007) (Ackland, Elliott, & Bloomfield, 2009). This results in a similar situation to that of training an amateur. In order to tailor a training program to a specific athlete, the knowledge about the fundamental aspects are needed. If the coach is unable to greatly alter the technique of an athlete, the changes that they are able to implement are of even greater importance. This is especially important if those small alterations could be the difference between the victory and loss of a professional athlete.

As outlined previously, a structured long-term training program is vital to the optimal development of an athlete. This type of program must continuously be adapted as the athlete progresses. A knowledgeable coach or trainer is therefore required to supervise the process, altering the program and providing feedback to the athlete (Ackland, Elliott, & Bloomfield, 2009). Information provided to the athlete concerning the action performed is one of the most important variables affecting the learning and subsequent performance of a skill (Ericsson, 2004) (Wulf, Mcconnel, Gartner, & Schwarz, 2002). Knowledge about the proficiency with which an athlete performs a skill is critical to the learning process and failure to provide such knowledge could result in the athlete not progressing at all. Further, it has been found that the quality of the information provided directly affects the skill acquisition process (Ericsson, 2004). Therefore, in order for a coach to adequately guide and develop a player, they require the understanding of both the process and outcomes of the movement involved (Ackland, et al., 2009). Such an understanding between outcomes and process are paramount, and relies on the ability of the coach or trainer to translate theory into practice.

"Current coaching practice is based on tradition, intuition and emulation rather than on empirical research" (Williams & Hodges, 2005, p. 637). However, several studies found that such observation is both unreliable and inaccurate (Hughes & Franks, 2004). Figure 1 shows the traditional coaching cycle. It can be seen that each aspect of the cycle has an effect on several other aspects of training and have compounding effects as the cycle is completed multiple times.

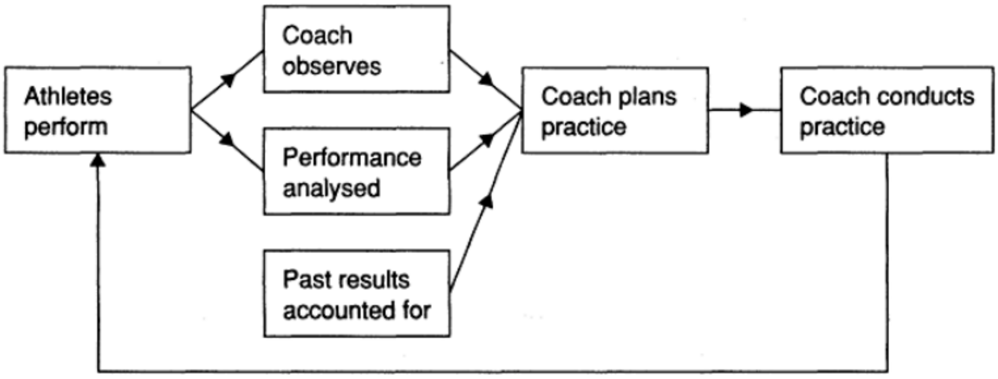

Figure 1: Simple schematic representing the coaching cycle *(Hughes & Franks, 2004)*.

In order to break the tradition of current coaching methods based on subjective observation, further means of analyses rooted in empirical evidence are required.

2.3 HUMAN MOVEMENT ANALYSIS

Movement is the means by which we interact with the environment, whether we are out for a stroll, taking part in a sporting event, or rehabilitating an injury. A thorough understanding of the various aspects of human movement can facilitate more effective coaching, training protocols and the formulation of new research ideas (Hamill, Knutzen, & Derrick, 2015). "Human movement analysis aims at gathering quantitative information about the mechanics of the musculo-skeletal system during the execution of a motor task. In particular, information is sought concerning the movement of the whole-body centre of mass; the relative movement between adjacent bones, or joint kinematics…" (Cappozzo, Della Croce, Leardini, & Chiari, 2005, p. 186). The two main aims of human movement analysis are the reduction of injury and the improvement of performance. Human movement analysis may occur in several different forms, from the observation of a coach using only the naked eye, to the intricate studies conducted using sophisticated laboratory equipment. Each method of observation serves its role based on the required outcome of the analysis (Bartlett, 2005).

2.3.1 Branches of Movement Analysis

Human movement analysis can be broadly separated into two branches of science: kinesiology and biomechanics (see Figure 2). Kinesiology focuses on “the musculoskeletal system, movement efficiency from the anatomical standpoint, as well as joint and muscular actions during simple and complex movements”. A typical analysis involves identifying discrete phases in an activity, describing the segmental movements occurring in each phase, and identifying the major muscular contributors to each joint movement. Most kinesiological analyses involve observing a movement, the investigation of the skills involved in the movement, and the identification of the muscular contributions to the movement. As a result, kinesiological analyses are considered being qualitative (Hamill, et al., 2015).

Biomechanics is “the study of the movement of living things using the science of mechanics” (Hatze, 1974, p. 189). The field of biomechanics provides the means of conceptualising and quantifying the forces and movement involved in understanding how living things move and how movements can be made safer or more efficient (McGinnis, 2013). Biomechanics can be applied over a wide variety of movements (Winter, 2009). For example, it allows us to understand why humans walk the way they do, what effect gravity has on the human musculoskeletal system, how mobility impairment in the elderly can be improved, and how prostheses can aid individuals with below-knee amputations. Sport bio-mechanists and engineers have also contributed invaluably to improving performances in selected sports. From playing surfaces and equipment, to shoes, biomechanics plays an important role in recognizing what practices are perhaps less effective and less dangerous, and how athletes optimize performance (Klavora, 2015) (Knudson D. V., 2007) (Winter, 2009) (McGinnis, 2013).

Biomechanics can be separated into three sub-components, namely functional anatomy, kinetics and kinematics. Functional anatomy is the study of the body components needed to achieve or perform a human movement or function (Hamill, Knutzen, & Derrick, 2015). It involves identifying the muscle or muscle groups involved in performing a movement or function, as well as determining the type of movement that is produced by the muscle or muscle group, e.g. flexion and extension, rotation (internal or external), abduction and adduction. Functional anatomy can be utilised by both biomechanical and kinesiological studies. Knowledge of functional anatomy is useful when setting up a training program and to assess the injury potential in a movement.

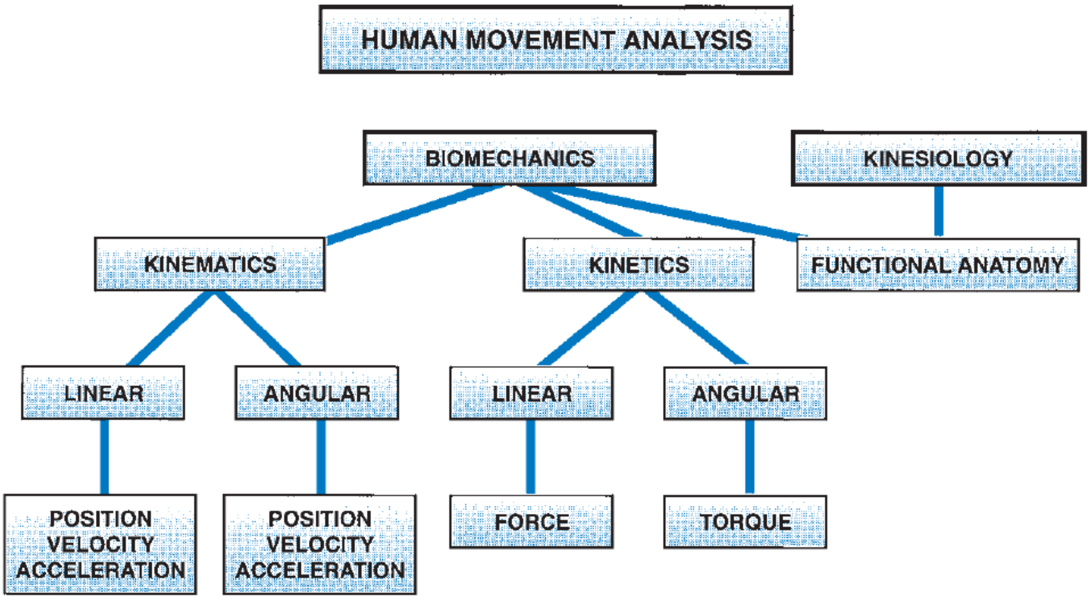

Figure 2: Components of biomechanical and kinesiological movement analysis *(Hamill, Knutzen, & Derrick, 2015, p. 5)*

Kinetics is an area of study that examines the forces acting on a system, such as the human body, or any object. A kinetic movement analysis examines the forces causing a movement. A kinetic analysis can provide valuable information about how the movement is produced or how a position is maintained. This can be used in the formulation of conditioning and training programs for a sport or movement. It also identifies positions where joints are the weakest, allowing further insight into the aspects of a movement or athlete that makes the athlete more prone to injury (Hamill, Knutzen, & Derrick, 2015). A kinetic analysis is much more difficult to comprehend and evaluate, as only the effects of the forces can be observed. The assessment of these forces poses the greatest challenge in biomechanics because it requires sophisticated equipment and considerable expertise.

Kinematics is defined as “study of motion” dealing with a body or system in motion without reference to the cause i.e. force. The phenomena (motions) rather than the cause (force) are the subject of analysis (measurement) in a kinematic study. Kinematic quantities of interest include position and orientation of the segments, positions of the joints and their time-derivatives (linear and angular velocities and accelerations) (Kwon, 2008). By examining an angular or linear movement kinematically, we can identify the segments involved in that movement that require improvement or obtain ideas and technique enhancements from elite performers or break a skill down into its component parts (Hamill, et al., 2015). This study aims to investigate the kinematics of various key joints and segments (e.g. knee and hip flexion and extension) that are of importance during the execution of a rugby goal kick.

2.3.2 Quantitative and Qualitative Movement Analysis

As stated earlier, human movement analysis comes in many forms with varying degrees of complexity. Two main approaches to human movement analysis can be identified, namely a qualitative- and quantitative analytic approach (Lees, 2002). Qualitative analysis of human movement is defined as the "systematic observation and introspective judgement of the quality of human movement for the purpose of providing the most appropriate intervention to improve performance" (Knudson & Morrison, 2002). Qualitative analysis is by nature a subjective process, and is based on the judgement and experience of the observer (Knudson D. V., 2013) (Klavora, 2015) or the analyst's (or equipment's) ability to recognise the vital aspects of the movement. Qualitative evaluations of movement will produce a description of the movement (Kreighbaum & Barthels, 1996).

The quantitative approach to analysing human movement on the other hand, is a data-driven numeric evaluation of the movement and is primarily performed in a research setting (Kreighbaum & Barthels, 1996). For example, biomechanics is strongly rooted in quantitative science and focuses on measuring the displacement and its time derivatives of certain segments of the body (McGinnis, 2013). A quantitative approach therefore eliminates subjectivity as the numerical data collected can describe or explain the physical situation (Kreighbaum & Barthels, 1996). Figure 3 shows the continuum of a human sprinting and shows that the qualitative side of sprinting includes the more non-numerical aspects of human movement analysis using aspects such as the developmental level of the athlete or subjective ratings as basis for evaluation. The quantitative side of the continuum involves parameters of performance that are more measurable and that can be expressed in numerical values, such as the acceleration or the forces present in joints (McGinnis, 2013).

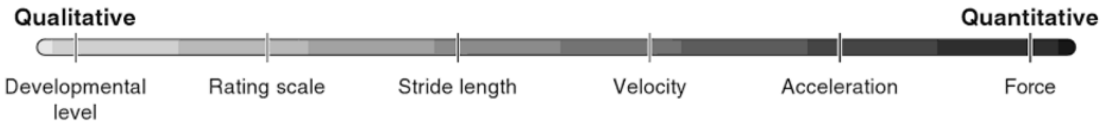

Figure 3: Sample continuum of human movement analysis *(Knudson & Morrison, 2002, p. 5)*

This research report has a greater focus on the quantitative side of the continuum, although no analysis can be either purely quantitative or qualitative and always involves elements of both (Knudson & Morrison, 2002) (Klavora, 2015).

2.4 BIOMECHANICAL ANALYSIS TECHIQUES AND TOOLS

Biomechanical analysis uses a mixture of experimental and theoretical approaches to analyse movements and are mainly interested in improving performance and reducing injury risk. Currently the two most prominent movement analysis techniques employed are videography (two-dimensional) and motion capture (three-dimensional) (Bartlett, 2007).

2.4.1 Videography (Two-Dimensional Analysis)

Videography is a rudimentary analysis tool used to record motion in a two-dimensional plane. The technology is cheap and easy to set up in both a laboratory and competition environment. It is ideal for the assessment of qualitative aspects of a movement, as it allows a coach or trainer to observe the movement performed at a later time, as well as at a slower rate. This technique is however not ideal for complex analysis, as most videography systems suffer from slow sampling rate and movement can only be captured in a predefined movement plane. In the case of intricate or high-speed movements, a considerable amount of data can be lost in the moments between each recorded frame (Bartlett, 2007).

2.4.2 Motion Capture (Three-Dimensional Analysis)

Although there are many different systems capable of accurately tracking the movement of the human body (Edmison, 2004), the use of optical motion capturing systems are considered to be the gold standard for quantitative human movement analysis (Menache, 2000). Most motion capturing systems involve some form of marker attached to the body that is tracked by some means (Mündermann, Corazza, & Andriacchi, 2006). Optical motion capturing systems such as the Vicon system used throughout this project, utilise infra-red light to track movement. The cameras serve as the light source, as well as the sensor, capturing the light that is reflected off reflective markers that is attached at key anatomical positions on the body.

The greatest advantage of the use of optical based tracking systems is that it allows the subject to freely move within a predefined capture volume without being restricted by cables attached to the body. This, coupled with the high frame rate and high degree of accuracy of such a system, means that it is ideal for the use of fast paced movements such as the rugby goal kick. Its largest drawback is however that in order to increase the capturing volume of the system, additional cameras must be added. As the system is generally quite expensive, it could result in the system being out of range for smaller research-based users (Furniss, 2016). The standard setup used by research groups involve a series of 6 to 10 cameras, spaced out to create a capture volume of approximately 8 m x 4 m x 2 m (length x breadth x height) (Cockcroft & Van den Heever, 2016). The system is capable of being scaled up to incorporate additional cameras with some systems utilising more than 300 cameras (Furniss, 2016).

In order for a marker to be tracked it must be visible to at least two separate cameras (Bartlett, 2007). The accuracy, however, is greatly improved by the addition of a third camera. This has the implication that in the case of intricate movements or movements involving additional obstacles that could obscure markers from the vision of the cameras, marker occlusion could occur. Each camera tracks the two-dimensional position of a marker. The system uses data from multiple cameras to triangulate the three-dimensional position of the marker within the capturing volume. This process is repeated for multiple frames per second, creating a sequence of global coordinates over time (Guerra-Filho, 2005).

2.5 THE BIOMECHANICS OF GOAL KICKING

In the section to follow, several key aspects regarding the biomechanics of the rugby goal kick are highlighted and discussed. The general sequence of movements performed during a standard goal kick is described, followed by the consideration of the success criteria in the context of a rugby goal kick. The section is concluded with the identification and discussion of the key performance indicators for the goal kick.

2.5.1 Kicking Sequence

Kicking motion is characterized by sequential motion of body segments (e.g. thigh and shank), progressing from the most proximal segment to the most distal segment and is described as a “proximal-to-distal sequential pattern”. “Each segment in a linked system influences the motion of its adjacent segments in a way that is dependent on how the segment is moving and how the segment is orientated relative to its adjacent segments” (Putnam, 1993, p. 125). Putnam (1993) identified the summation of speed principle as one of the most important principles underlying the description of proximal-to-distal sequencing in sport movements is the summation of speed principle. The principle states that, in order to achieve the greatest possible distal speed, the movement should be initiated by the most proximal segment and progress down the kinetic chain towards the most distal segment (The Performance Lab Inc., 2014). Figure 4 illustrates the summation of speed principle in a typical throw, showing how each segment initiates motion at the instant that the more proximal segment achieved its greatest speed.

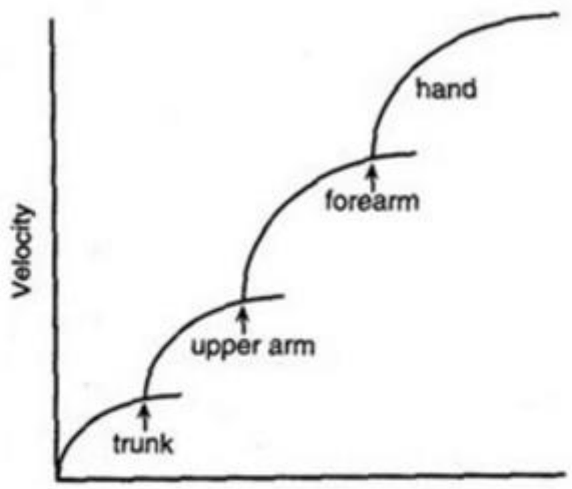

Figure 4: Summation of speed principle in a standard throw. Each successive distal segment begins accelerating when the contiguous, proximal segment reaches its maximum
(https://theperformancelabinc.wordpress.com/2014/09/16/the-kinematic-sequence)

Almost all kicking skills require maximum speed to be achieved at the end of a distal segment in a kinematic chain (Fowler, 2005). Describing the motion of the sequence using either the joint angular velocities or the segment angular velocities leads to an appreciation of how each joint or segment contributes to the final speed of the most distal endpoint in the system. In order to quantify the angular velocity of both the joint and segment, the kinematic information of the more proximal segment and joint must be known. Expressing a proximal-to-distal sequence in such a way lends to easier visualization of the movement since we typically think of motion as a series of joint rotations (Putnam, 1993).

However, when segments move in sequence, the more proximal segments do not significantly contribute to the maximum speed reached at the most distal end at the instance of impact. The histories of these individual segments enable the more distal segments to achieve greater speeds through the principle of the summation of speeds. This can be seen in Figure 4 where the more proximal segments start to decelerate at the instance when the more distal segment accelerates.

The rugby goal kick is very similar to that of the in-step kick utilised in soccer penalty kicks, however, several factors differentiates the two. The lack of a goalkeeper in rugby as well as the different shape of the ball used alters the rugby goal kick slightly. The rugby kick also differs to that of other similar kicks used in other sports by allowing a teammate of the kicker to hold the ball in place, similar to that of the goal kick in American football, or make use of either a kicking tee or sand (Zhang, Liu, & Xie, 2012). This allows the kicker to elevate the ball slightly and alter the orientation, further controlling ball contact. Figure 5 illustrates the use of a kicking tee.

Figure 5: Orientation of a rugby ball placed on a kicking tee *(BBC, 2016)*

Similar to that of the in-step kick utilised in soccer (see Figure 6) the rugby goal kick is defined by several phases and events. During the approach phase, players build up speed in the body by taking one to five strides towards the ball. The player approaches from an angle, orientating the body to facilitate more pelvis rotation during ball contact. The orientation also causes the body to tilt, lifting the kicking side hip to compensate for the flexion of the support leg, which effectively lowers the body. This tilt allows for favourable foot position during ball contact. The final stride during this approach consists of a leap that is usually much longer than the previous strides. The leap is initiated by driving of off the kicking side leg, launching the kicker towards the ball. The moment which the kicker loses contact with the ground is defined as K2. During the launch phase, the kicker rotates the hip backwards, creating a large range of motion for the kicking leg. The moment that the supporting side foot is planted next to the ball is defined as S2 and signals the end of the launch phase and the beginning of the kick phase. The kick phase lasts from the support leg contact (S2) until contact is made with the ball (defined as K3). During the kick phase the forward motion of the kicking leg is initiated by a proximal-to-distal movement of the hip and thigh. The forward rotation is initiated by pelvic rotation about the hip of the supporting leg following the rotation of the thigh through hip flexion. The knee of the kicking leg continues to flex until it reaches maximal allowable flexion after which it begins to extend forward as the thigh reaches a vertical orientation. As the thigh starts to decelerate just before ball contact, the shank rapidly accelerates forward, reaching full extension at ball contact. The kicking leg remains fully extended throughout the early stages of the follow through until the knee begins to flex (Atack, Trewartha, & Bezodis, 2014) (Bezodis, Trewartha, Wilson, & Irwin, 2007).

Figure 6: Sequence of the in-step kick utilised in soccer (http://footballmedicine.net/rectus-femoris-biomechanics-during-soccer-kick-performance/).

2.5.2 Performance Indicators

The success of a rugby goal kick is determined by whether the ball travels through the goal posts (Figure 7a), located on either side of the field. The position, relative to the goal post, from which the kick must be attempted from, depends in the source of the attempt, i.e. where the try has been scored or the penalty rewarded. Figure 7b shows the positions of all the attempted goal kicks during the 2015 Rugby World Cup. In the case of a scored try, the kicker is allowed to move the kicking position in a straight-line perpendicular to the try line at the position where the try has been scored. For a penalty, the kick is attempted from the position where the penalty is given (World Rugby House, 2016). Both the distance the ball must travel and the angle at which it is attempted will therefore differ from kick to kick. This variability in kicking position and distance puts a great deal of demand on the skills of the kicking player. The variability of the kicking position increases the difficulty of quantifying the performance of a kick, creating the need to understand the effects of variability in distance and accuracy on the desired movement required to reach a positive outcome.

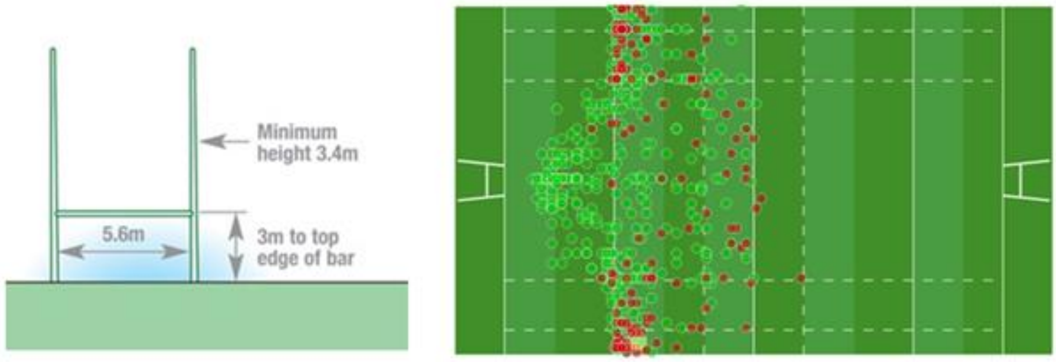

Figure 7: (a) Standard rugby union goal post dimensions (World Rugby House, 2016)**. (b) Positions of all attempted goal kicks in the 2015 Rugby World Cup** (http://goalkickers.co.za/)

To conclude, the two largest performance indicators of a successful goal kick are the velocity of the ball post ball contact and the directionality of the ball trajectory (Linthorne & Stokes, Optimum projection angle for attaining maximum distance in a rugby place kick., 2014). An important skill for an athlete is the ability to generate ball speed without sacrificing accuracy. Several studies concluded that the velocity of the ball strongly correlates to the velocity of the foot at ball contact (Padulo, Granatelli, Ruscello, & Dottavio, 2013) (Baktash, Hy, Muir, Walton, & Zhang, 2009) (Lees & Nolan, 1998). The velocity of the ball post contact is therefore dependant on the ability of the athlete to generate sufficient kinetic energy from the body and efficiently transferring the energy from the body to the ball (Baktash, et al., 2009). Traditionally the ratio between ball speed, after ball contact, and foot speed before ball contact, is defined as the Transfer Efficiency of the kick (Simons, 2016). The athlete generates kinetic energy in the body, transferring the energy in a proximal-to-distal sequence to the ball (Zhang, Liu, & Xie, 2012). Just generating foot speed is however not enough; athletes are required to transfer the speed from the foot to the ball in the most efficient manner possible. Transfer efficiency is therefore the first off field variable that can be determined in a laboratory environment.

Another important determinant of the performance of the kick, the directionality of the kicked ball, is directly determined by the position the kick is attempted from. The manner in which kinetic energy is transferred from the foot to ball, does not only affect the ball speeds generated, but also the direction of ball travel after ball contact has been made. The direction of travel is determined by analysing the speed vector of the ball. A study done by Linthorne and Stokes investigating the optimal elevation angle for attaining maximum distance in a rugby place kick, found that the angle at which the ball travels post ball contact, greatly affects the distance travelled by the ball (Linthorne & Stokes , 2014). The elevation angle resulting in the maximum ball velocity was found to be 30^0. The elevation velocity that a player can produce decreases substantially as the elevation angle is increased, reducing the optimal angle to be well below the assumed 45^0.

To summarise, the performance of the kick can be determined by the ball speed (by extension the transfer efficiency and foot velocity) and the directionality of the ball (by extension the directional transfer from the foot to the ball). However, in order to enhance the performance of goal kickers, it is not only necessary to know the performance variable of the kicking action, but also which sequences of motion contributes the most to achieving the required performance variables (see Section 2.5.1) (Lees, 2002). These motion sequences are invaluable to practically and objectively determine guidelines to be implemented by coaches and trainers (Simons, 2016).

2.6 THE PROCESSING OF KINEMATIC DATA

The measurement of kinematic data always has some form of error attached to the signal. These errors are referred to as noise and occupy an undesirable portion of any waveform. These errors in measurement are caused by soft tissue artefacts, improper digitization of retro-reflective markers and electrical interference (Winter, 2009).

Traditionally the noise introduced in kinematic data is of a higher frequency than the true signal and can be removed using various smoothing and curve fitting techniques; the most common filtering technique being digital filtering (Challis, 1999) (Winter, 2009). Digital filtering functions by attenuating the higher frequency region of the signal, removing the noise component from the signal without affecting the true signal. The most common digital filter used for kinematic data is a low-pass Butterworth filter. When using a low-pass filter the cut-off frequency is selected so that the lower frequencies remain, yet the higher frequencies are attenuated (Sinclair, Taylor, & Hobbs, 2013). When implementing a standard Butterworth filter, some phase distortion occurs, causing the data to shift. To eliminate this phase lag, “Butterworth filters can be modified to become zero-lag filters when the data are processed in both the forward and reverse directions” (Robertson & Dowling, 2003, p. 569). In addition to eliminating any phase shift delay, the bi-directional filtering produces a sharper cut-off and is termed a fourth-order zero-lag shift filter.

“If the relevant frequency content of the raw signal is known, numerous methods are available to distil the relevant signal. However, in movement analysis it is often unknown which part of the frequency content represents the actual movement” (Schreven, Beek, & Smeets, 2015, p. 808). This leaves the decision around the cut-off frequencies to the discretion of the researcher. Traditionally the cut-off frequency is selected by means of visual inspection. This is however not a feasible practise as it is susceptible to human judgement and can be a time consuming endeavour when multiple signals need to be processed (Challis, 1999). With the introduction of high-speed digital computers and a growing demand for detailed and accurate information in human engineering and medical science, more intricate and sophisticated methods of filtering and smoothing have been developed. Several of these algorithms that use defined objective criteria for the determination of an appropriate cut-off frequency will be discussed in a later section (see Section 2.7).

The following three factors have been identified to have an influence on the selection criteria for an appropriate frequency: soft tissue artefacts, ill-posedness of time-derivative estimations and the inherent smoothness of human movement. The effects they have on the filtering choice will be discussed further in the following sections.

2.6.1 Soft Tissue Artefacts

The largest source of error in the capturing of kinematic data is caused by the effects of soft tissue artefacts. “It is caused by the erroneous assumption that markers attached to the skin surface are rigidly connected to the underlying bones”. “Inertial effects, skin deformation and sliding, gravity and muscle contraction interdependently contribute to this phenomenon” (Stagni, Fantozzi, Capello, & Leardini, 2005, pp. 320,321). The frequency of these artefacts is usually similar to that of the bone/skeletal movement and can therefore not be distinguished by means of any filtering technique. However, in the case of any external influence on the movement, such as interaction between the body and an object, a higher frequency rippling is propagated through the segments of the body (Schinkel-Ivy, Burkhart, & Andrews, 2012). As the rippling effect occurs at a frequency higher than that of the knee movement and is localised to the period after ball contact, an approximation of the rippling signal can be made.

2.6.2 Ill-Posedness of Time-Derivative Estimation

The estimation of time derivatives of kinematic data is an ill-posed problem, meaning that “the quantities being estimated are highly sensitive to certain types of errors in the measurements” (Woltring, 1985, p. 230). The ill-posedness of kinematic data can be illustrated by showing the effects of an additive sinusoidal term $ASin(\omega t)$, with very small amplitude A, and a very large frequency ω. In the measured data, the effect of this additional term is negligible, however, the amplitude of the differentiated error term (ωA) may be large enough to contaminate the original signal. This is especially a problem when the signal is “contaminated with wide-band measurement noise, which can be modelled in terms of a sum of many low-level, high frequency sinusoids” (Woltring, 1985, p. 231).

This is best illustrated with a simple example. Take for example a sinusoidal signal with an amplitude of 1 and a frequency of 1Hz. Add to this signal an additional sinusoidal signal with an amplitude of 0.01 and a frequency of 10 Hz, representing additive noise. Equations 1 to.3 and Figure 8 show the amplification effects of the noise component. Looking at the original signal, the noise does not seem to have any significant effect on the overall shape of the signal, however, by the second derivative the amplitude of the noise has grown to such an extent that previously insignificant noise now has the same amplitude as that of the original clean signal.

$$X(t) = 1\sin(1t) + 0.01\sin(10t) \tag{1}$$

$$\frac{dX(t)}{dt} = 1\cos(1t) + 0.1\cos(10t) \tag{2}$$

$$\frac{d^2X(t)}{dt^2} = -1\sin(1t) - 1\sin(10t) \qquad (3)$$

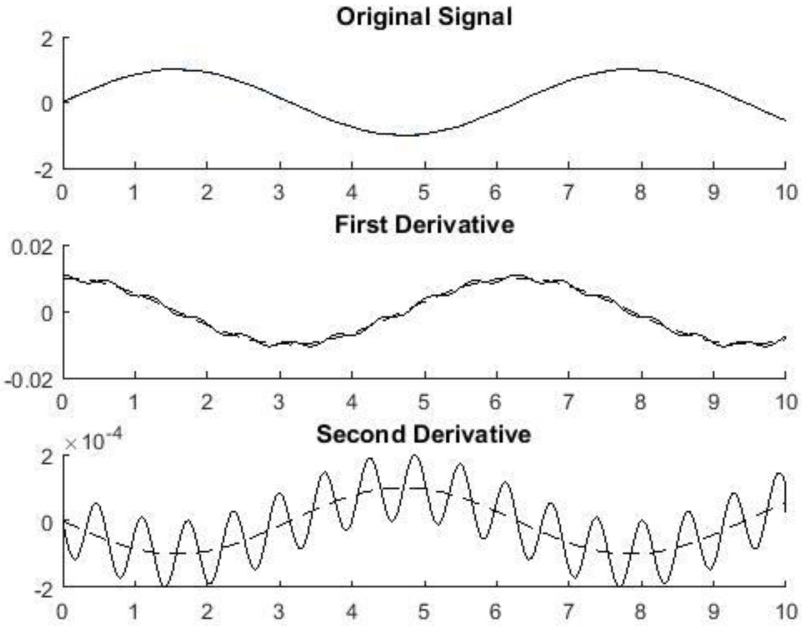

Figure 8: The amplification effect of high frequency additive noise on a signal. Solid line indicating the clean signal with added noise and the dashed line indicating the clean signal. (a) Zero-derivative, (b) First-derivative and (c) Second-Derivative

Due to this amplification effect, additional constraints must be included to arrive at meaningful derivative data. That is, the movement must be sufficiently smooth. This means that it cannot contain exceedingly high frequency components, since the opposite would entail too high inertial forces to facilitate the rapid change in position or direction.

2.6.3 Inherent Smoothness of Human Kinematics

Empirical observations made by Krylow and Rymer (1997, p. 165) have shown “that practiced, target-directed, voluntary limb movements that are executed at high speeds display a high degree of smoothness in their movement trajectories. Smoothness of multi-segmental movement is usually quantified using higher order derivatives of motion, including the third-time derivative of endpoint displacement (or ‘jerk’)”. According to Newton’s second law; $F = ma$, force and acceleration have proportional relationships when the mass is fixed. Therefore, jerk can be defined as the variation of applied force (Choi, Joo, Oh, & Mun, 2014).

Any object with mass in motion will attempt to resists the effects of external influence on its motion. This inertia property serves as a smoothing effect. This also holds true for the movement of the musculoskeletal system. The intrinsic properties of active muscle tissue, could serve as dampeners, smoothing out movement, even in the absence of programmed neural inputs. The mechanical filtering properties of muscle, effectively removes the effects of high frequency components during movement. Furthermore, an examination of the recorded load position versus time profile reveals that the motion of the load produced by the muscle force is of very simple form, and is quite smooth. The velocity profile of the motion is similarly smooth, exhibiting a progressive increase (Krylow & Rymer, 1997).

2.7 AUTOMATIC FILTERING ALGORITHMS

Using statistical or power spectrum information, automatic filtering algorithms attempt to estimate an ideal filtering frequency for a recorded signal. These techniques remove the need for operator intervention, as the results do not need to be inspected before proceeding to the next iteration (D'Amico & Ferrigno, 1990). A major shortcoming of automatic filtering techniques is the fact that they cannot be applied universally. Due to the nature of different kinematic data, filtering techniques that provides adequate filtering results when implemented on a specific data set cannot be assumed to be adequate for a different data set. For this reason, several techniques must be applied to determine which method is ideal for a specific signal (Giakas & Baltzopoulost, 1997).

Three different automatic filtering techniques have been identified as the most commonly used with regards to kinematic data, namely cumulative power analysis, residual analysis and regression analysis (Giakas & Baltzopoulost, 1997). Cumulative power analysis is based on estimating the frequency wherein a specified percentage of the signal’s power is present. Residual analysis compares the residual between the filtered signal to that of the raw data to determine an appropriate cut-off frequency. Regression analysis utilises a regression model to calculate an appropriate cut-off frequency, using the sampling frequency as an initial input and an error value for additional refinement.

2.7.1 Cumulative Power Analysis

The first filtering technique involves performing a cumulative power analysis of the marker data using a fast Fourier transform (FFT) to examine the cumulative content of the signal in the frequency domain. Fourier analysis converts a signal from its original domain to a representation in the frequency domain and vice versa (Giakas & Baltzopoulost, 1997). Frequencies in the Fourier transform are spaced out at intervals of F_S/N, where F_S is the sampling frequency and N is the length of the input time series. In the case of the rugby goal kick data, the frequency intervals are larger than desired. This results in large errors in the estimation of the different frequency elements of a signal, as multiple elements can overlap at the frequency points. This is referred to as spectral leakage (Lyon, 2009).

Zero padding is an effective way to help improve the accuracy of amplitude estimation. Zero padding is a simple technique that pads the time-domain signal with additional zeros at the end of the signal, effectively increasing the length of the signal. An increase in the length of the signal will result in a smaller frequency interval of the Fourier transform. For example, by adding 9N zeros to the end of a signal, the distance between two adjacent frequency bins become $F_S/10N$ since the signal now has a length of $10N$ samples. Figure 9 shows a comparison between the FFT of the unfiltered Right Knee angle before and after zero-padding was implemented.

The power (PW) of each component of the spectrum is calculated by squaring the amplitude (AM). However, since the time-domain signal was padded with additional zeros, the calculated powers are reduced by a factor of $N/(N+L)$, where N is the number of zeros that have been added and L is the new length of the signal, zeros included. The inverse of this factor is applied to the power calculation to obtain the true powers of the nonzero data.

$$PW = AM^2 \Big/ \frac{(N+L)}{N} \tag{4}$$

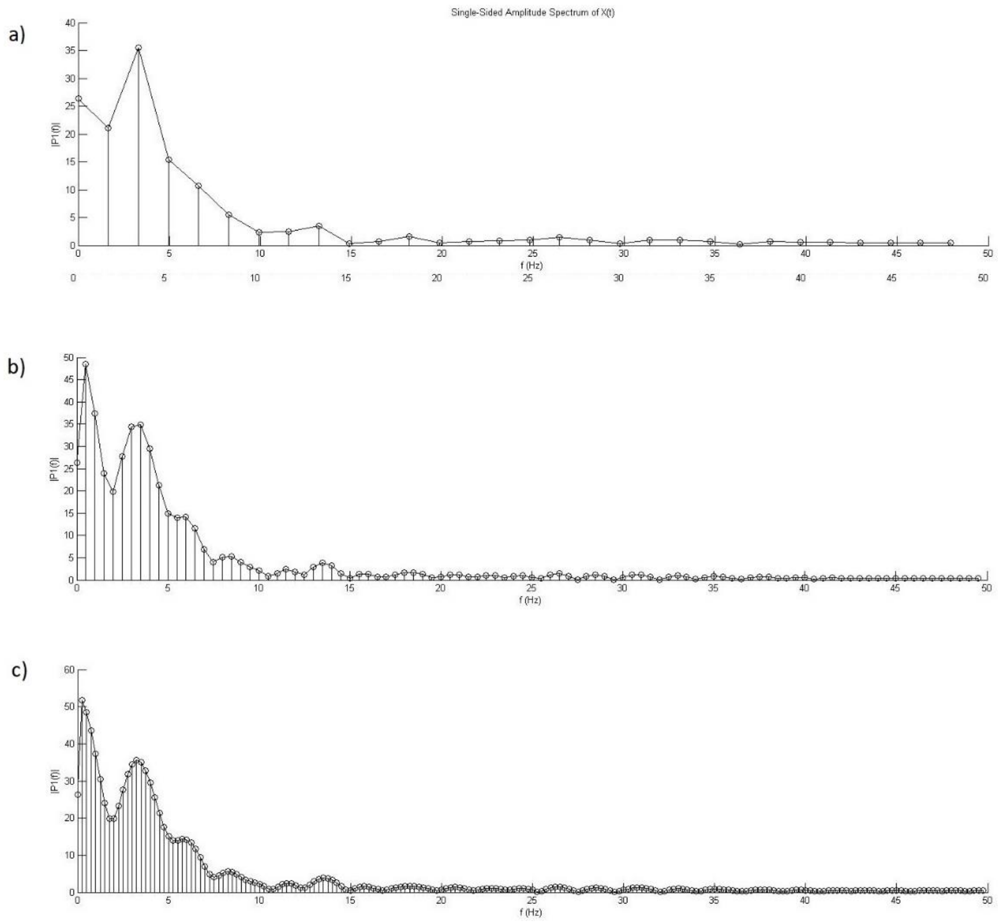

Figure 9: Fast Fourier Transform of Right Knee angle (a) without zero-padding, (b) zero-padding with a 0.5 Hz frequency interval and (c) zero-padding with a 0.25 Hz frequency interval

FFT allows the identification of the frequency of a signal in the presence of noise. It is known that the true kinematic data is located at the lower frequency components of the signal and therefore the accumulative content of the signal can be used to determine a suitable cut-off frequency. Typically, the choice of cut-off is taken as the frequency at which 95 or 99% of the signal power is contained (Sinclair, Taylor, & Hobbs, 2013). Figure 10 shows an example of the cumulative power of a signal.

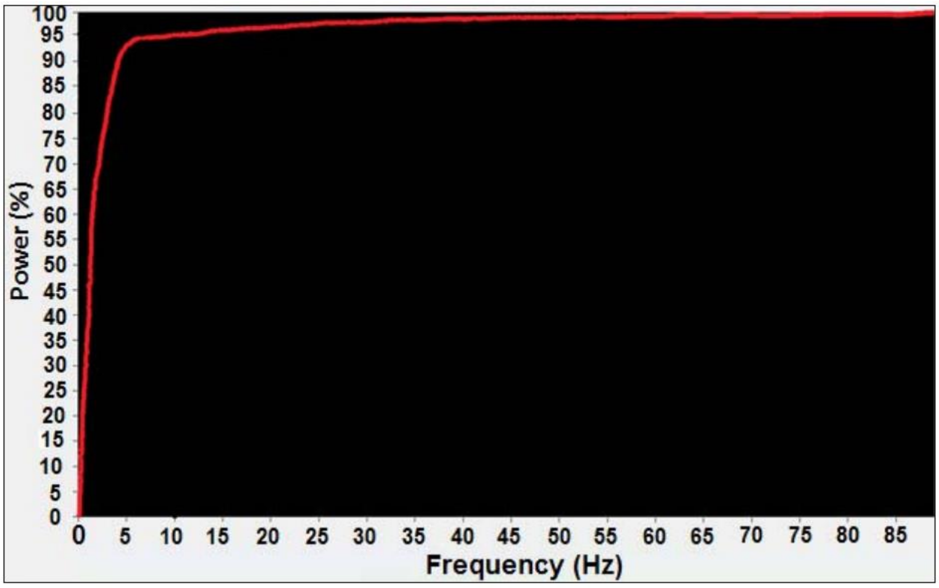

Figure 10: Example FFT cumulative power analysis of marker information *(Sinclair, Taylor, & Hobbs, 2013, p. 26)*

2.7.2 Residual Analysis

The second filtering technique involves performing a residual analysis – a technique developed by Winter (2009). Residual analysis examines the differences between the raw and filtered kinematic pattern over a pre-set range of cut-off frequencies. The term residual refers to the signal content that remains when the filtered data is subtracted from the raw data. The residual at any cut-off frequency is calculated as follows for a signal of N sample points in time:

$$R(fc) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(X_i - \hat{X}_i)^2} \tag{5}$$

where fc is the cut-off frequency of the fourth-order dual-pass filter, X_i is the raw data at the *i*th sample and $\hat{X}_i$ is the filtered data at the *i*th sample using a fourth-order zero-lag filter. Figure 12 shows a theoretical plot of residual versus frequency (Winter, 2009).

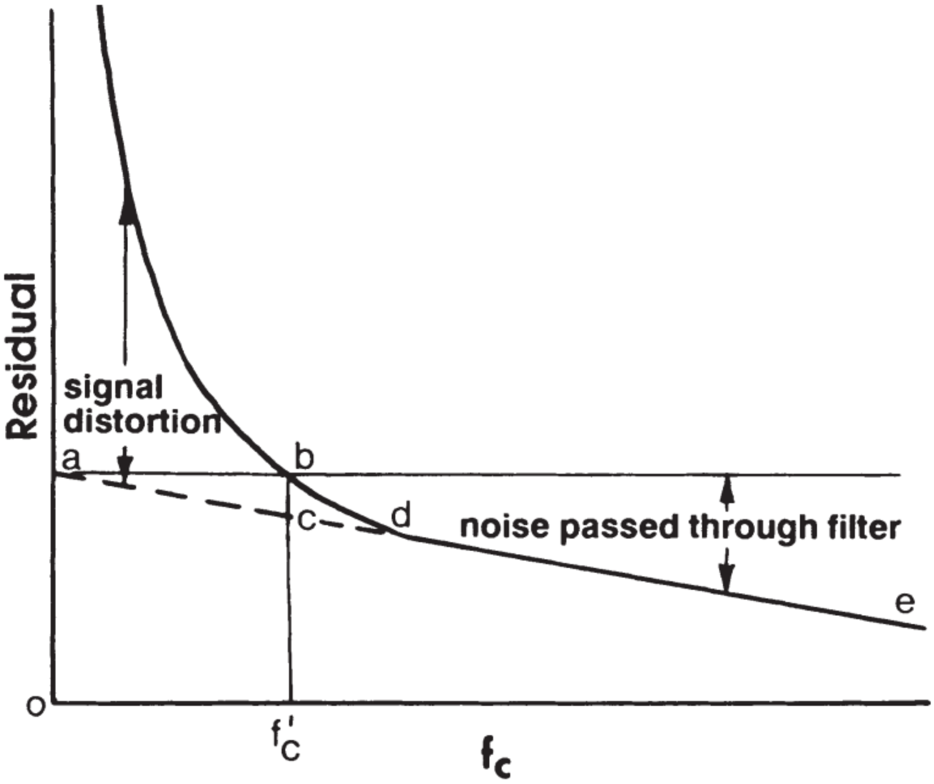

Figure 11: Plot of the residual between a filtered and an unfiltered signal as a function of the filter cut-off frequency *(Winter, 2009, p. 71)*

As the frequency content of random noise would be evenly spaced throughout the entire frequency band, the accumulative residual between the filtered and unfiltered data would indicate a straight line. The reason for this is that the magnitude of each frequency component remains relatively constant. The plot of the residual would span from the intercept at 0 Hz to an intercept on the abscissa at the Nyquist frequency (half of the sampling frequency). The line *de* represents our best estimate of the noise residual. When data consist of a true signal combined with noise, the effects of the filtering process would distort the signal causing a sharp rise in the residual value. The effects on the residual increases as the cut-off frequency is reduced and a larger portion of the signal is affected, the corresponding residual plot will rise above the straight line (*de*) (Winter, 2009).

As the choice of the cut-off frequency is a trade-off between the distortion caused to the signal and the amount of noise that is allowed to remain in the signal, Winter (2009) proposes a simple choice of balancing the two values equally. To achieve this, he proposes that a horizontal line is drawn from *a* too *b*, where the residual line is intercepted (see Figure 12). The cut-off frequency recommended is the frequency corresponding to the position of point *b* and the amount of distortion applied to the signal is represented by the difference between point *b* and *c.* (Winter, 2009).

2.7.3 Regression Analysis

The third filtering technique of importance is regression analysis. The general purpose of multiple regression is to learn more about the relationship between several independent or predictor variables and a dependent or criterion variable (StatSoft, Inc, 2013). A multiple regression analysis was conducted by Gabriel, Yu, Noble and An (1999) to estimate the mean optimum cut-off frequency for a given sampling frequency. A second-order regression model was used to express the optimum cut-off frequency as a function of the sampling frequency

$$f_{c,1} = C_0 + C_1 f_s + C_2 f_s^2 \tag{6}$$

A backward elimination procedure was used to determine the best regression equation. After the best regression equation was determined, the mean optimum cut-off frequency for the given sampling frequency was estimated from the sampling frequency, filtering x_n at that cut-off frequency, resulting in a filtered data set X_n. The relative mean residual, ∈, between x_n and X_n was determined as

$$\in = \sqrt{\frac{\sum_{n=0}^{N}(X_n - \acute{X}_n)^2}{\sum_{n=0}^{N}(X_n - \bar{X})^2}} \times 100\% \tag{7}$$

where $\bar{X}$ was the mean of X_n. This relative mean residual, ∈, was used as an approximation of the mean noise-to-signal ratio of the raw data. A second multiple regression analysis was conducted to determine the effects of f_s and ∈ on the optimum cut-off frequency.

A pilot study conducted by Yu (1988) showed that the optimum cut-off frequencies for a given sampling frequency were fitted by an unbounded function of the mean noise-to-signal ratio. Therefore, the regression model for the second regression analyses was in the form of

$$f_{c,2} = D_0 + D_1 f_s + D_2 f_s^2 + D_3 \frac{1}{\in} \tag{8}$$

A backward elimination procedure was again used to determine the best regression equation.

Using the arm angular kinematic data collected by Pezzack, Norman, and Winter (1977), the estimated optimum cut-off frequency is tested. Three sets of computer-generated random errors were added to the angular kinematic data to create three sets of raw data with significant random errors. Each set of raw data was filtered through the Butterworth low-pass digital filter at an estimated optimum cut-off frequency.

It was found that the optimum cut-off frequency was significantly correlated with the sampling frequency. The best regression equation for the relationship between the optimum cut-off frequency and the sampling frequency was

$$f_{c,1} = 0.071 f_s - 0.00003 f_s^2 \tag{9}$$

The relative mean residual (∈) determined by Equation 7 contributed significantly to the prediction of the optimum cut-off frequency. The best regression equation for estimating the optimal cut-off frequency from f_s and ∈ was

$$f_{c,2} = 0.06 f_s - 0.000022 f_s^2 + 5.95 \frac{1}{\in} \tag{10}$$

6.1.1.1 *Protocol for estimating optimum cut-off frequency*

Yu (1988) developed a protocol for estimating optimum cut-off frequency. The protocol involves the following steps:

1. Given the sampling frequency, estimate the mean optimum cut-off frequency using Equation 9.
2. Filter the raw data at the estimated mean optimum cut-off frequency.
3. Calculate the relative mean residual between the filtered data and raw data using Equation 7.
4. Estimate the final optimum cut-off frequency using Equation 10.
5. Filter the raw data using the second estimate of optimum cut-off frequency to have the filtered output.

6.1.1.2 *Protocol validity*

The above described protocol was developed using regression models and based on only one kind of angular kinematic data, namely arm angular kinematic data. Therefore, the accuracy of the estimated optimum cut-off frequencies may not be guaranteed when the protocol developed is applied to other kinds of kinematic and kinetic data. However, the protocol has been applied to filter another set of data that was not used in the development of the protocol, and the accelerations calculated from the filtered coordinate data essentially matched the actual acceleration curve (Gabriel, Yu, Noble, & An, 1999)

In addition, Giakas and Baltzopoulos (1997) showed that the regression equation developed by (Yu, 1988) estimated cut-off frequencies reasonably well from the sampling frequency for several different raw data sets. These results provide further support for the validity of this protocol for other kinds of kinematic and kinetic data.

2.8 CHAPTER SUMMARY

This chapter started off by discussing the acquisition of skills and the need for structured practice. This is followed by a discussion on the different approaches to human movement analysis, biomechanical analysis and its sub-fields. The specific biomechanical techniques and tools relevant to this study were thereafter introduced. The last section of the chapter introduced the biomechanics of goal kicking in rugby, kinematic data and ended by introducing various approaches to automatic filtering. In the next chapter the methodology of the study is discussed.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 INTRODUCTION

This chapter introduces the research methods used to generate and analyse the kinematic data obtained from fifteen professional rugby union kickers. With the support of SARU, fifteen professional rugby union goal kickers participated in the study. At the time of recording the data, all participants played at either national or international level. Ethical clearance for the project was obtained from Stellenbosch University's Human Research Ethics Committee and all ethical protocols such as written informed consent by the participants, were implemented.

3.2 PARTICIPANTS

The general characteristics of the participants are described in Table 2. Each participant was deemed healthy at the time of testing and did not suffer from a prior injury that would alter the execution of the rugby goal kick. None of the participants participated in any strenuous endurance and/or resistance training prior to testing, outside that of their regular training protocol. All participants tested are right-side dominant.

Table 2: General characteristics of the participants

	Height (m)		**Weight (kg)**		**Age (years)**	
	Average	**Range**	**Average**	**Range**	**Average**	**Range**
Participants	1.79	1.72 – 1.91	87	82.4 – 93.3	26.4	20 - 32

3.3 DATA COLLECTION

The collection of data was conducted by Dr J Cockcroft and Dr D van den Heever as part of the larger project described in Chapter One (Cockcroft S. J., 2015) (Cockcroft & Van den Heever, 2016). Data was collected indoors in the motion analysis laboratory of Stellenbosch University. At the time of testing, the Motion Analysis Unit of the University of Stellenbosch did not possess the required equipment to conduct testing in an outdoor setting. The indoor setting in the laboratory presents an unusual surface and target to the participants as the floor in the laboratory was constructed from hard rubber. Participants were instructed to perform the test kicks wearing their own running shoes instead of standard rugby boots to prevent them from slipping on the hard rubber of the laboratory (Cockcroft & van Heever, 2016).

Each participant performed their own stretching and warm-up routine before the marker placement. Participants completed several warm-up kicks before they were recorded. This allowed them to acclimatise to the possible discomfort caused by the smooth floor and kicking in running shoes.

Ten consecutive goal kicks were captured for each participant, using their own kicking tee and a single pre-selected premier league Gilbert rugby ball. The kicking effort was requested to be for a mid-range (submaximal) distance goal kick. The target was defined by two strips of tape that simulated the goal posts on a wall behind a steel framed net. (See Figure 12 for an illustration of the test set-up used by Cockcroft and van Heever (2016) during the collection of the data.) Participants consequently performed complete goal kicks (run-up and kick at self-selected speed and intensity) towards the target. The kicking tee was placed on a predefined position to ensure that the non-kicking support leg (SL) foot consistently landed on a Bertec force plate imbedded in the floor. Any reflective materials in the participant's shoes and clothing were covered with tape to prevent any false marker detections. Along with this, any possible environmental sources of infra-red reflection were also either removed or masked.

An 8-camera Vicon MX system was used to capture the kinematic data of the participants. Data was captured synchronously in the Vicon Nexus software (version 1.8.4) and the Bertec force plate at 200 Hz and 1000 Hz respectively. The capture volume of approximately 4 m x 4 m x 2 m (L x W x H) covered both the run-up and the follow-trough area of the kicker. The Vicon cameras were calibrated dynamically using the standard dynamic 5-point wand waving procedure before the start of every test (Cockcroft & van Heever, 2016).

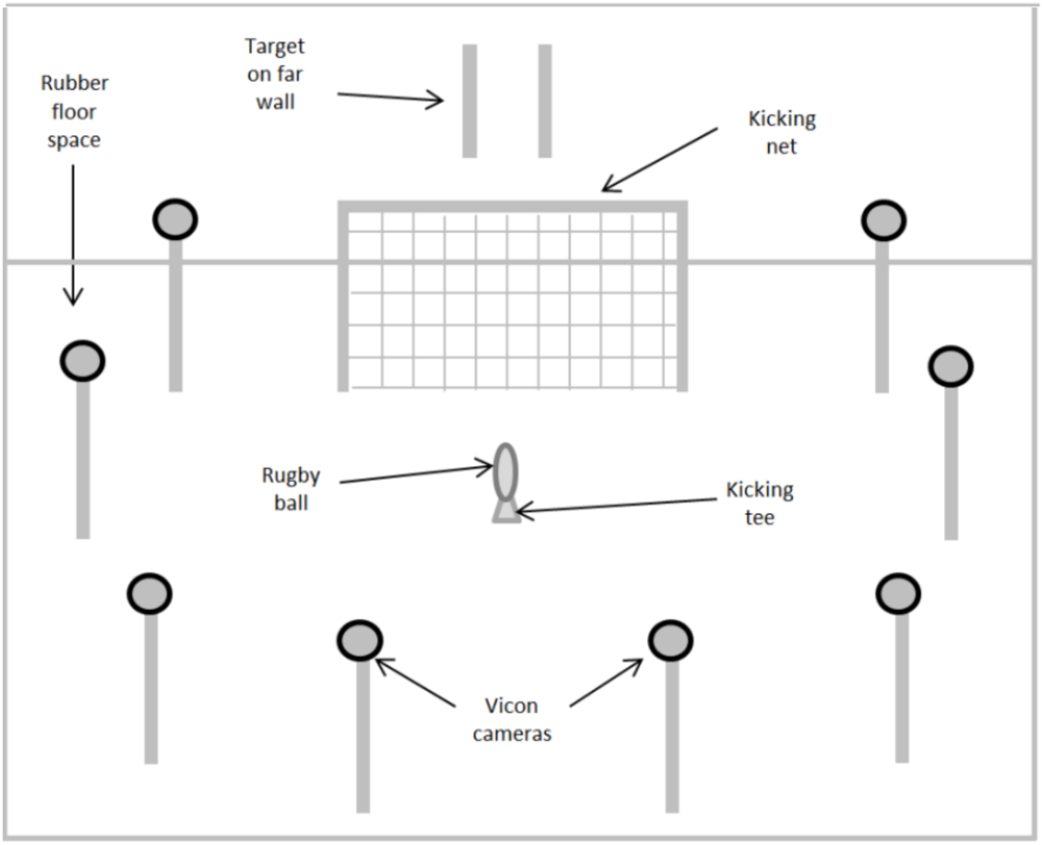

Figure 12: Schematic of test set up showing Vicon camera positions relative to ball, net and target *(Cockcroft & Van den Heever, 2016)*

Cockcroft and van den Heever (2016) made use of standard passive reflective Vicon markers (14 mm diameter) which they placed on the participants' bodies, following a modified plug-in-gait model (Figure 13). Four markers were placed on the kicking leg shoe, namely a heel marker, a toe marker, an ankle marker (placed on the lateral malleolus) and a lateral marker placed mid-way along the length and height of the shoe (called the reference marker). The additional ankle and reference markers on the kicking foot were required to track the kicking foot toe marker during the kick as it was not clearly visible in the Vicon cameras near impact with the ball. During a Vicon static calibration trail, the measured position of the toe marker relative to a coordinate system (defined by the measured heel, ankle and reference markers) was determined. In the dynamic kicking trials, the heel, ankle and reference markers were used to estimate the toe marker position, overcoming camera occlusion. Additional markers were placed on each side of the ball approximating the midpoint of the ball, as well as on the tee. The midpoint position of the ball was used to determine the moment of impact with the ball (Cockcroft & van den Heever, 2016). Once a kick was recorded, the marker trajectories were reconstructed and labelled using standard pipeline operations in the commercial

Vicon Nexus software. From there, the data is exported to Matlab (version 9.2.0.538062, R2017a) for further analysis.

Because of missing marker information concerning the Right ELB and the ball & tee, one right-footed player and one left-footed player could not be used for further analysis. In total, 10 trials of 12 athletes were used for data processing. For one player, only 9 successful kicks could be used because the RTHI marker was missing for one of the trials, leading to a sample of 119 kicks to be analysed.

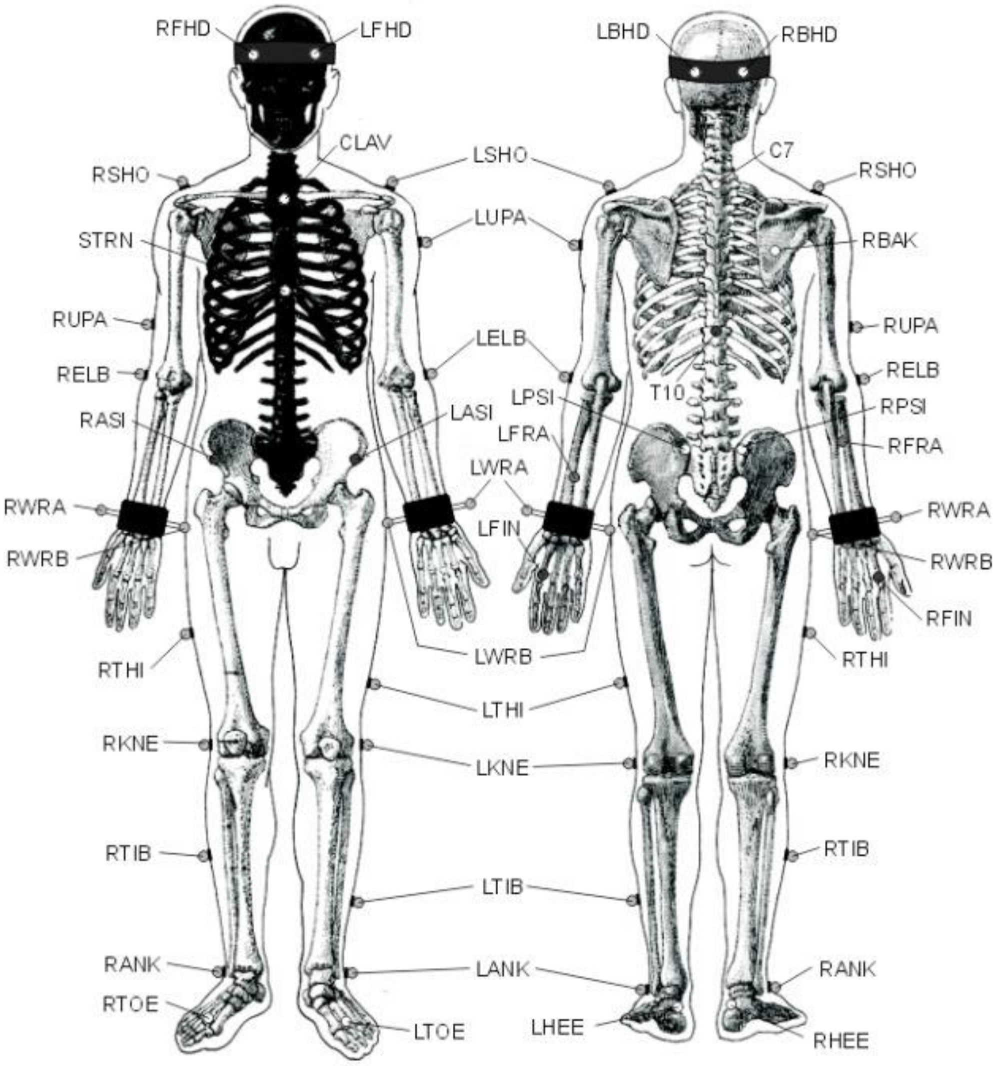

Figure 13: A figure showing the marker placement for the Plug-in-Gait marker biomechanical model from the IDMIL webpage *(Plug-in-gait marker placement)*

3.4 DATA ANALYSIS

After collecting the Vicon data, several processing steps were executed in Matlab. The analysis consisted of two parts: identifying and applying a filtering protocol, followed by the extraction of key kinematic properties of a goal kick.

3.4.1 Filtering

The kinematic data were filtered using a fourth-order zero-lag low-pass Butterworth filter, to attenuate the high frequency noise. The cut-off frequency used for the filter dictates the amount of noise that remains in the signal, but can also cause some of the signal to be lost. The angular data for several joints of interest for the study were filtered at frequencies between 5 and 15 Hz and at intervals of 2.5 Hz. The time derivatives of the angular data were calculated using a second order central difference method. Both the angular data and the angular velocity were plotted (see e.g. Figures 18 & Figure 19). The effects of the different cut-off frequencies were visually inspected in order to determine the ideal filtering frequency range for each of the joints.

Three automatic filtering algorithms (cumulative power analysis, residual analysis and regression analysis) were applied to the joints and the calculated cut-off frequencies were compared to that of the theoretical ideal cut-off frequencies found through visual inspection. The automatic filtering algorithms tested were discussed in more detail in Chapter 2. Once the theoretical ideal cut-off frequency for each of the different joints and markers has been determined, the data of all of the participants were filtered at their respective frequencies. This data was used to determine and prepare the kinematics and sequence of each participant.

3.4.2 Events

As each participant has the freedom of choosing their starting positions and run-up distance, the number of steps utilised during the kick differs from participant to participant. A means of standardising the kick was therefore needed to ensure that the same movement-information is present in each recorded kick. Throughout the kick several key events and phases were identified and used as means of defining the progress of the kick. Foot-off and foot-contact of both legs were predefined with the Vicon Nexus Software. Despite the variation in kicking styles, all the athletes demonstrated a set pattern before ball contact (see Table 3 for a description of each event and Figure 14 for the sequence of events).

Table 3: Description of events observed during a goal kick

Event	Abbreviation	Description
Support leg off	S1	Non-kicking side foot lifted off of the ground during the final preparatory step.
Kicking leg contact	K1	Kicking side foot makes contact with the ground during the final preparatory step.
Kicking leg off	K2	Kicking side foot lifts off of the ground, initiating the launch phase.
Support leg contact	S2	Non-kicking side foot is planted next to the tee after the launch phase.
Kicking leg ball contact	K3	Kicking side foot makes contact with the ball.
Support leg off	S3	Non-kicking side foot lifts off of the ground during the follow-through, signalling the end of the kick.

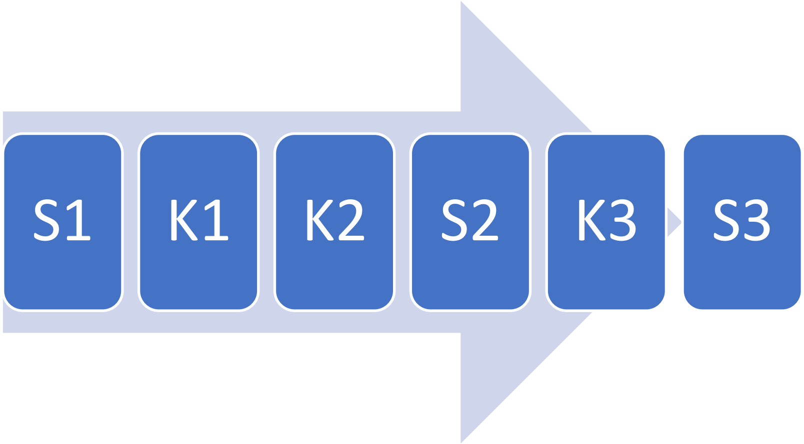

Figure 14: The common sequence of events observed during a goal kick

3.4.3 Time Standardisation

The length of each kick was cropped with either S1 or K1 (depending on which phase occurs first) being the start of the kick and S3 being the end. Even with the defined phases and events, the duration of each kick differs. In order to accurately compare kicks, the events must be time or frame normalized. This was achieved by expressing the timing of the kick on a percentage scale from 0 to 100%. The actual data was however not resampled, as this would cause some distortion of the relative timing and pace of the different kicking phases.

3.4.4 Segmental Kinematics

The segmental kinematics was calculated using the Vicon PiG model of the Vicon Nexus software. Key kinematic properties, such as maximum and minimum flexion angle and maximum and minimum joint angular velocity of each segment was determined, along with the timing of when these properties occur. Segmental interaction was investigated by comparing the order and time in which each segment reaches their maximum angular velocity.

3.4.5 Missing Markers

Missing markers present a challenge to data collection. In the event that the cameras lose sight of one of the markers, the data of that marker could still be estimated using interpolation techniques, given that the period the markers were not visible still falls within the allowable range. However, if there are too many markers missing, the data is unusable.

3.4.6 Ball Kinematics

In order to track the movement of the ball post ball contact, three markers were placed on the rugby ball. Two markers were placed on either side of the ball where its diameter is the largest, while the third marker was placed on the top of the ball. The markers placed on the ball are prone to detach from the ball due to contact with the kicking foot. In the case were one marker detached from the ball, the remaining two were used to triangulate the position of the third. This was however not always the case as there were some cases where there was not enough data to accurately track the motion of the ball. A further challenge posed by the rugby ball is that of flight rotation. Due to the oval shape of a rugby ball, it is prone to rotate during flight. In order to eliminate the effects of the rotation, the centre of the ball was calculated from the markers placed on the ball.

As a check, ensuring that the one of the markers attached to the ball has not come loose during the kick, the distance between the two markers that are placed on the ball is calculated while the ball is stationary. The distance of the two markers for each frame was compared to the stationary distances calculated and the error between the two values were used to determine whether they are still fixed to the ball. A threshold of 5% of the calculated distance was used to accommodate for measuring error or deformation of the ball during impact. In the case that the error becomes too large, it was deemed that the markers have separated from the ball and measurement of the ball kinematics was no longer possible.

Along with the possibility of the markers detaching from the ball during impact, the size of the capturing volume caused difficulty in the tracking of the ball. As the ball contact area is relatively close to the edge of the capturing volume and the rugby ball travels at high speeds, the number of usable frames for the tracking of the ball was very limited. Due to these difficulties in measuring, the ball speed for some of the kicks could not be calculated and were omitted during the reporting on the results found. The velocity of the ball is calculated by taking the time derivative of the positional data in each of the Cartesian axes. The magnitude of the velocity is then determined by

$$V_m = \sqrt{V_x^2 + V_Y^2 + V_Z^2} \tag{11}$$

with V_m being the magnitude and V_X, V_Y and V_Z being the calculated speeds in the three directions.

The transfer efficiency of each of the participants was calculated by dividing the ball speed generated by a participant with the foot speeds generated. The angle at which the ball travels post ball contact was determined by tracking the change in horizontal and vertical position for several frames after ball contact. The angle between subsequent frames was calculated and an average of the values was used as the final value.

3.5 CHAPTER SUMMARY

In this chapter, the characteristics of the participants were presented. The data collection procedure pertaining to the capturing of the three-dimensional biomechanical data of the rugby goal kick were discussed in detail. This was followed by a discussion on the filtering approach and the analysis of the biomechanical data set. The results and findings are present in Chapter 4.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 INTRODUCTION

This study has a twofold aim: testing the validity of several automatic filtering algorithms and analysing the kinematic sequence displayed during the rugby goal kick. In order to accomplish both of these aims, the effect of applying different filtering frequencies on data of importance to this study will be investigated. It is important to note the two assumptions made during the process of establishing the ideal filtering frequencies. As stated in Chapter 2, human movement is inherently smooth, meaning that any rapid change in position or direction during a movement is highly unlikely to occur, unless caused by an external source. It could therefore be concluded that, if there is indeed a sudden change or spike present in the data, it is most likely caused by either soft tissue artefacts or an error in the recording process.

Additionally, the noise present in the joint angular data would not greatly alter the general shape of the signal. Only once the derivative of the data has been taken and the noises have been amplified will it become prominent and affect the shape of the signal. Therefore, in the case were the filtered data greatly strays from the unfiltered joint angular data, it is most likely altering the signal itself. Similarly, if the filtered data fails to remove or greatly attenuate the effects of the amplified noise, the filter is considered to be too lax. It is therefore important to find the ideal midway between removing as much noise as possible without affecting the pure signal.

The following section contains the investigation process for determining the ideal filtering frequencies for: knee and hip flexion/extension, thorax and pelvis rotation and foot and ball movement.

4.2 FILTERING EFFECTS ON VARIOUS PARAMETERS

4.2.1 Knee Flexion and Extension

The knee joint is the final major joint in the kinematic chain used to propel the foot forward during a kicking movement. As shown in Figure 15, a positive angle indicates that the knee is in flexion and an increase in angle indicates that the knee is bending. The zero-degree angle indicates that the knee is fully extended, with a negative angle indicating that the knee went into hyper-extension.

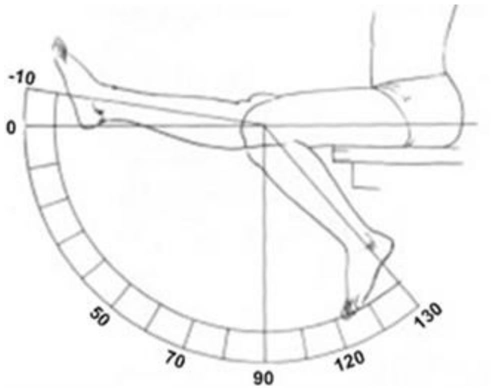

Figure 15: Knee flexion and extension sign convention

Figure 16 shows an example of the knee flexion angles during one of the recorded rugby goal kicks. The angular data has been filtered at various frequencies ranging from 5 to 15 Hz, at intervals of 2.5 Hz. As seen from Figure 16, the knee is almost locked out when the participant launches forward and flexes the knee until it reaches full flexion just after the support leg is planted next to the ball. From this position, the knee is rapidly extended to make contact with the ball. In some cases, the knee continues to extent farther until it hyperextends just after ball contact. It is however unknown whether this hyperextension is natural, or whether it is caused by the effects of soft tissue artefacts caused by the collision between the ball and the foot or the contraction of the thigh muscles.

Figure 17 shows the time derived velocity data of the filtered data in Figure 16. In this case a positive angular velocity represents the extension of the knee joint. The variation between the data filtered at different frequencies is much more evident in the velocity plot than it was in the angular plot. This is due to the ill-posedness of time derived data as discussed in Chapter 2. The figure shows the velocity profile of the knee that is rapidly brought extended towards ball contact.

As seen in Figure 16, the angular data filtered at 5 Hz and to some extent the data filtered at 7.5 Hz starts to deviate from the unfiltered data. As the noise in the angular data does not have as large of an effect on the shape compared to that of its time derivatives, it can be assumed to a relative high degree of confidence that the unfiltered angular data still represents the shape of the true signal. It is therefore believed that the 5 and 7.5 Hz data started to attenuate the true signal.

When observing the angular velocity data in Figure 17 it can be seen that the data filtered at 12.5 and 15 Hz starts to ‘follow’ the spikes caused by the amplified errors in the angular data. This most likely indicates that the laxer filters are allowing unwanted noise to contaminate the true signal. Based on these observations, the ideal cut-off frequency for the knee joint angular data is approximately 10 Hz. The data filtered at 10

Hz seems to follow the general form of the unfiltered angular data, while not being influence by the noise present in the data.

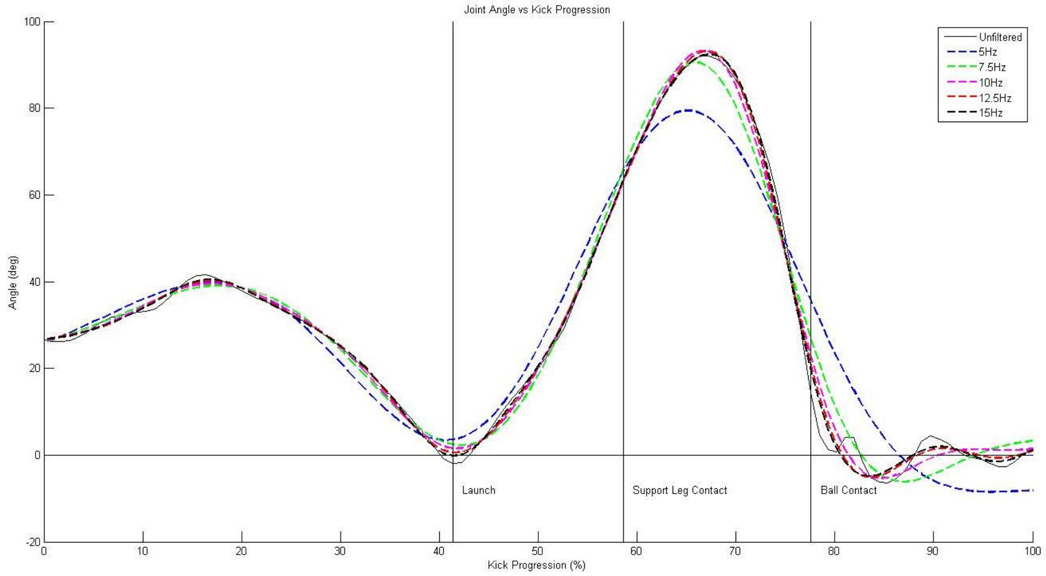

Figure 16: Knee flexion and extension during the rugby goal kick, filtered at frequencies ranging from 5 to 15 Hz.

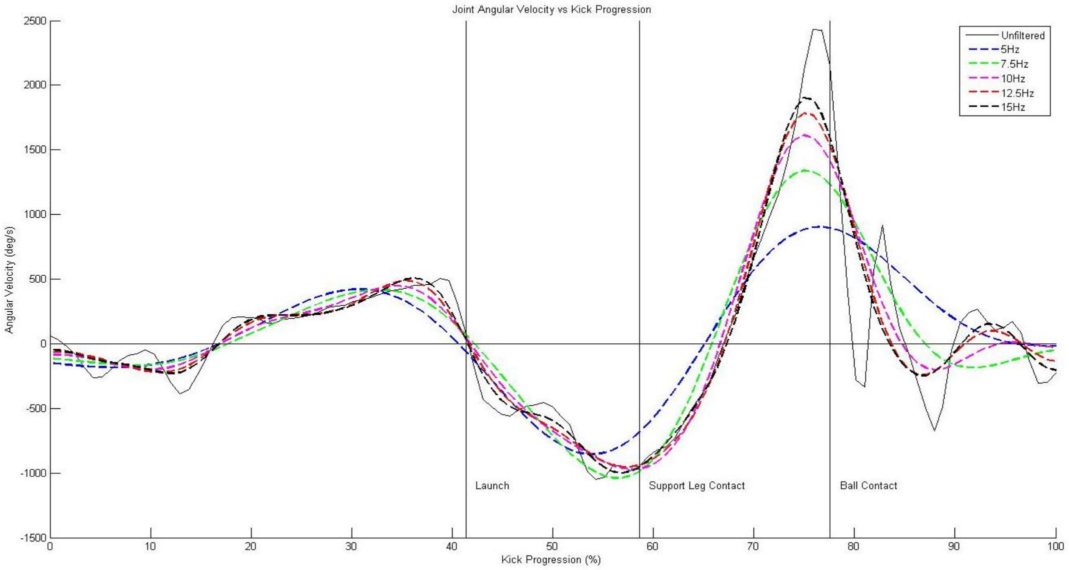

Figure 17: Knee angular velocity during the rugby goal kick, filtered at frequencies ranging from 5 to 15 Hz.

The effects of using different filtering frequencies on the measured peak knee angular velocity are shown in Table 4. As shown in Figure 15, as the cut-off frequency is lowered, the peak of the velocity is smoothened out, reducing the maximum value. The changes in peak angular velocity between the various filtering frequencies are shown in Table 5. The difference between the data filtered at 12.5 Hz and the data filtered at 15 Hz is rather small; the difference only being 129.57 deg/s (SD = 36.88). This is a change of less than 10% of the peak value. Similarly, the difference in peak angular velocity between the 10 and 12.5 Hz filtered data is only 167.16 deg/s (SD = 42.06). The difference in peak values increase greatly between the 7.5 and 10 Hz as well as the 5 and 7.5 Hz signals. This may indicate that the filtering process is altering the data to too large of a degree.

Table 4: Peak knee angular velocity filtered at frequencies ranging from 5 to 15 Hz

	Unfiltered	5 Hz	7.5 Hz	10 Hz	12.5 Hz	15 Hz
Mean	2475.93	1031.24	1467.61	1722.35	1889.51	2019.09
SD	437.18	146.84	218.54	245.00	265.52	286.88

Table 5: Variation in peak knee angular velocity filtered at frequencies ranging from 5 to 15 Hz

	5 - 7.5 Hz	7.5 - 10 Hz	10 - 12.5 Hz	12.5 - 15 Hz
Mean	436.37	254.74	167.16	129.57
SD	80.25	46.24	42.06	36.88

4.2.2 Hip Flexion and Extension

Hip flexion and extension involve large powerful muscle groups, capable of exerting large amounts of force. Shown in Figure 18 is the sign convention used when analysing the movement of the hip. A positive hip angle indicates that the hip is in flexion, meaning that the hip is rotated forward towards the chest of the person. A negative value indicates that the hip is in extension, with the hip rotated towards the back of the person.

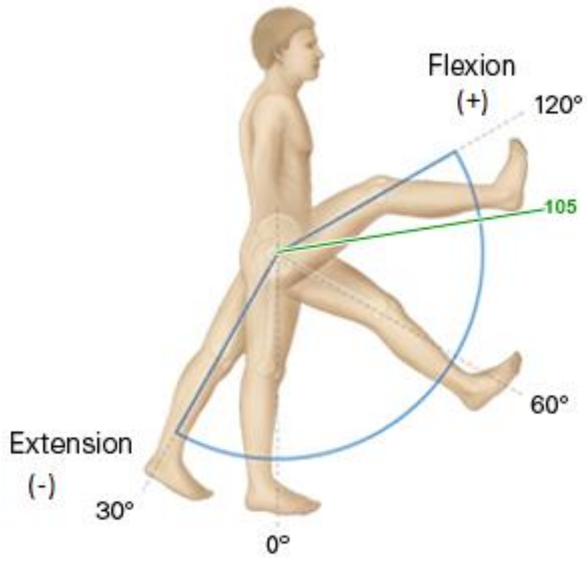

Figure 18: Hip flexion and extension sign conventions

Shown in Figure 19, is an example of the hip flexion and extension data during a rugby place kick. The data has been filtered at frequencies ranging from 5 to 15 Hz at intervals of 2.5 Hz. As seen from the figure, the hip flexes from a neutral position when the participant launches himself forward to a fully flexed position approximately when the support leg is planted next to the ball. From this position the hip is rapidly flexed until a point where it goes into extension just before ball contact. As the knee joint reaches full extension the hip follows, flexing during the follow-through.

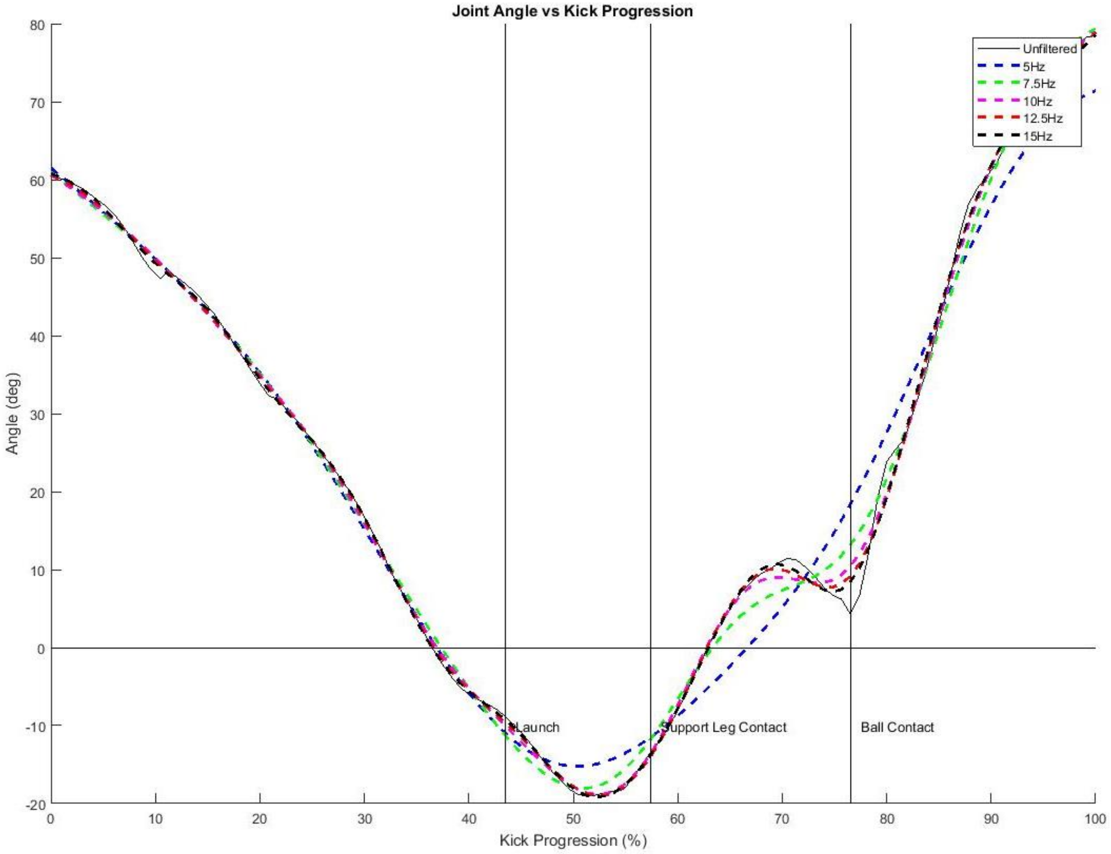

Figure 19: Hip flexion and extension during the rugby goal kick, filtered at frequencies ranging from 5 to 15 Hz

The velocity profile of the events discussed is shown in Figure 20. The figure shows the time derivative of the filtered data shown in Figure 19. The rapid forward movement and subsequent decrease in velocity of the hip can be seen between the support leg contact and ball contact events. As seen in both figures, the frequency at which the data is filtered has an effect on the deceleration period of the hip joint. At higher frequencies the plot shows that the direction of hip motion changes from flexion to extension during the decreasing velocity phase. As the cut-off frequency is reduced the peaks are smoothed out and the backwards rotation is reduced. It is unclear whether the hip does indeed rotate backwards, but by analysing high-speed camera footage of the motion capturing process, there are substantial movement of the thigh markers during this period. The error caused by these moving markers can directly affect the calculation of the hip and knee angles. The effect that the differing filtering frequency has on the peak angular velocity is shown in Table 6.

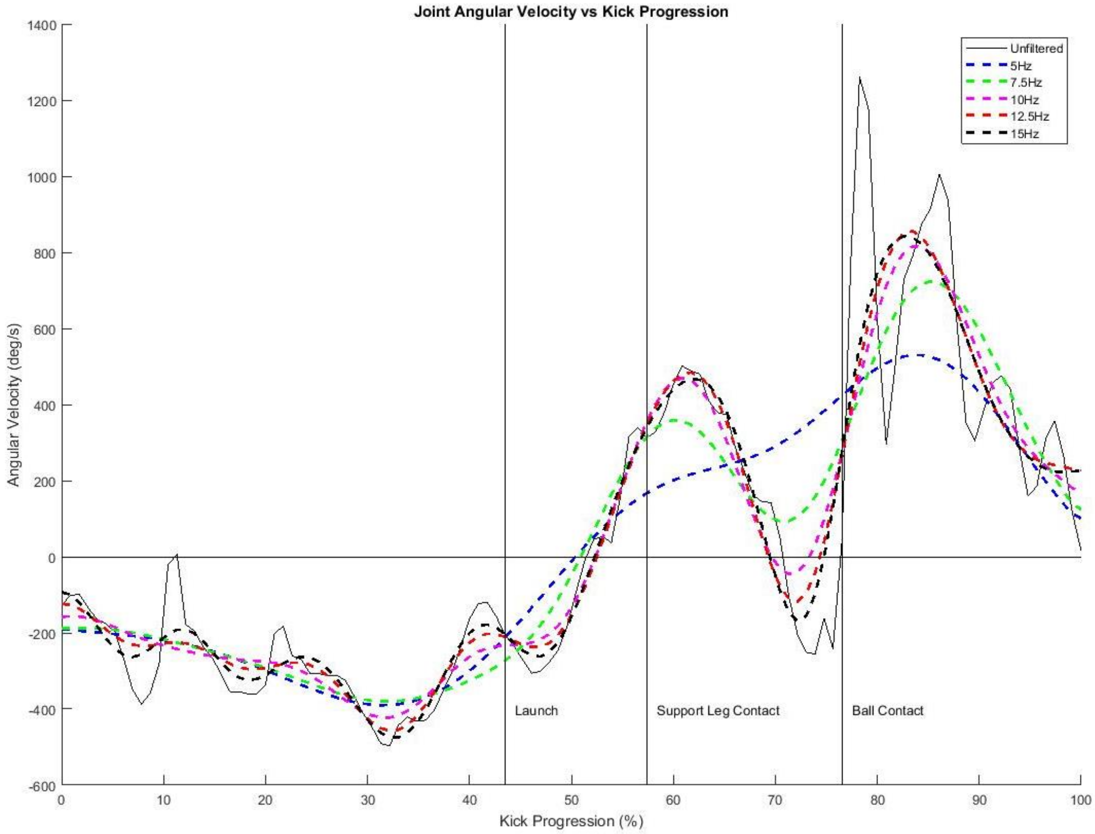

Figure 20: Hip joint angular velocity during a kick filtered at frequencies ranging from 5 to 15 Hz

The angular data filtered at 5 and 7.5 Hz starts to greatly deviate from the unfiltered data, indicating that the stricter filters are starting to attenuate the true signal. Additionally, inspecting several kicks, the negative velocity during the deceleration phase is filtered to have a value close to zero, when applying a cut-off frequency of 10 Hz. If the assumption is made that the hip does indeed not rotate backward during this phase, the ideal cut-off frequency for the hip extension and flexion is approximately 10 Hz.

Table 6: Peak hip angular velocity filtered at frequencies ranging from 5 to 15 Hz

	Unfiltered	5 Hz	7.5 Hz	10 Hz	12.5 Hz	15 Hz
Mean	645.00	425.54	469.11	559.53	591.28	598.89
SD	131.42	61.84	80.69	95.55	99.52	107.23

In contrast to the velocity of the deceleration phase, the magnitude of the peak prior to this phase is not largely affected by the choice of cut-off frequency, as shown in Table 7. The difference in magnitude between the data filtered at 12.5 and 15 Hz is as low as 7.62 deg/s and the difference between the 10 and 12.5 Hz data is only 31.75 deg/s. When filtering at frequencies lower than 10 Hz, the peak is smoothed out significantly, lowering the magnitude of the peak. The small difference in amplitudes between the data filtered at 10 to 15 Hz indicates that even if the assumption of a continuously positive hip velocity is incorrect, the error caused is minimal.

Table 7: Variation in peak hip angular velocity filtered at frequencies ranging from 5 to 15 Hz

	5 - 7.5 Hz	7.5 - 10 Hz	10 - 12.5 Hz	12.5 - 15 Hz
Mean	43.57	90.42	31.75	7.62
SD	102.44	44.78	27.78	22.10

4.2.3 Thorax rotation

The thorax angle calculation is especially susceptible to the effects of soft tissue artefacts and marker occlusion. This is due to the nature of the anatomical landmarks where the reflective markers are fixed to the body. These landmarks are in areas where there are a lot of soft tissue and a lot of movement, causing large spikes in the angular data. These spikes or discontinuities greatly affect the time derivatives of the angular data and can only be lessened or removed by applying relatively strict filters to the data. Fortunately, the strictness of the filtering process does not affect the peak angular velocity of the thorax to a large extent.

An example of the rotation of the thorax during a rugby goal kick is shown in Figure 21. The angular data has been filtered between 5 and 15 Hz at increments of 2.5 Hz. A negative value indicates that the thorax is rotated in the clockwise direction; with zero degrees being the neutral position with the thorax squared with the forward direction towards the target.

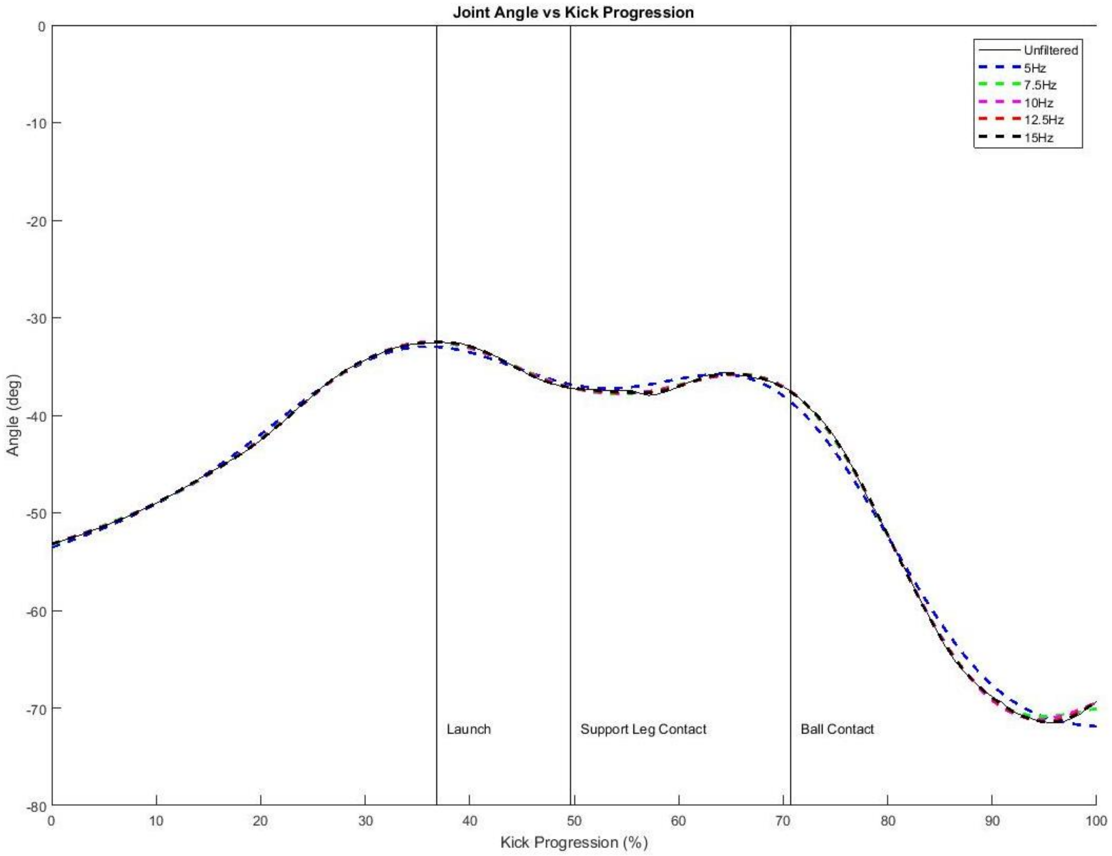

Figure 21: Thorax rotation angle during the rugby goal kick, filtered at frequencies ranging from 5 to 15 Hz

As seen in Figure 21, the participant retains a negative angle throughout the duration of the kick; this is due to the angled approach made by many kickers. Figure 22 shows the rotational angle of the thorax when the angled approach is removed by applying a 2 Hz fourth order high-pass Butterworth filter. From this, the angle of the thorax relative to the forward movement of the body can be visualised in an easier to understand form. It clearly shows the participant ‘opening up’ the upper body from the launch until the support leg is planted next to the ball, followed by a rapid closing as the kicking leg is brought forward for ball contact. An example of this action can be seen in Figure 23.

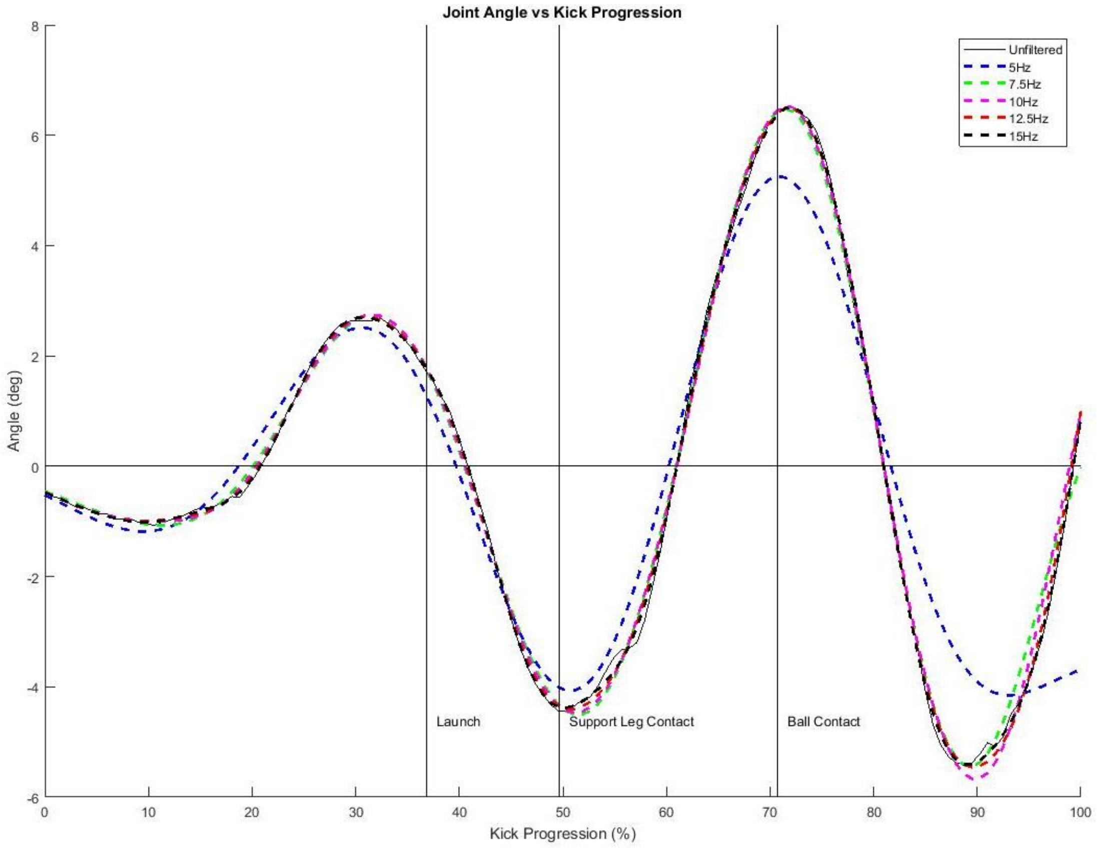

Figure 22: Thorax rotation about the direction of travel during a rugby goal kick, filtered at frequencies ranging from 5 to 15 Hz

Figure 23: Thorax rotation during launch and ball contact phases (http://www.bbc.co.uk/guides/zw2djxs)

Figure 24 shows the time derived angular velocity of the filtered data of Figure 21. The figure shows the angular velocity of the thorax due to the ‘opening’ and ‘closing’ of the upper body discussed above. It shows the peak velocity obtained just prior to the ball contact.

When observing the effects that the filtering has on both the angular data and the velocity data, the effects of over and under smoothing can be seen. The angular data filtered at 5 Hz visibly deviates from the unfiltered data. This deviation leads to the conclusion that the data should be filtered at a cut-off frequency that is greater than 5 Hz. In contrast, the angular velocity data of the data filtered at 12.5 Hz and 15 Hz tend to follow the effects of the errors and spikes in the data. The difference between the data filtered at 7.5 Hz and 10 Hz are very similar and it is unclear whether filtering at either frequency negatively affects the shape of the signal. It is therefore likely that the ideal cut-off frequency for the filtering of the thorax rotational data is in the range of 7.5 to 10 Hz.

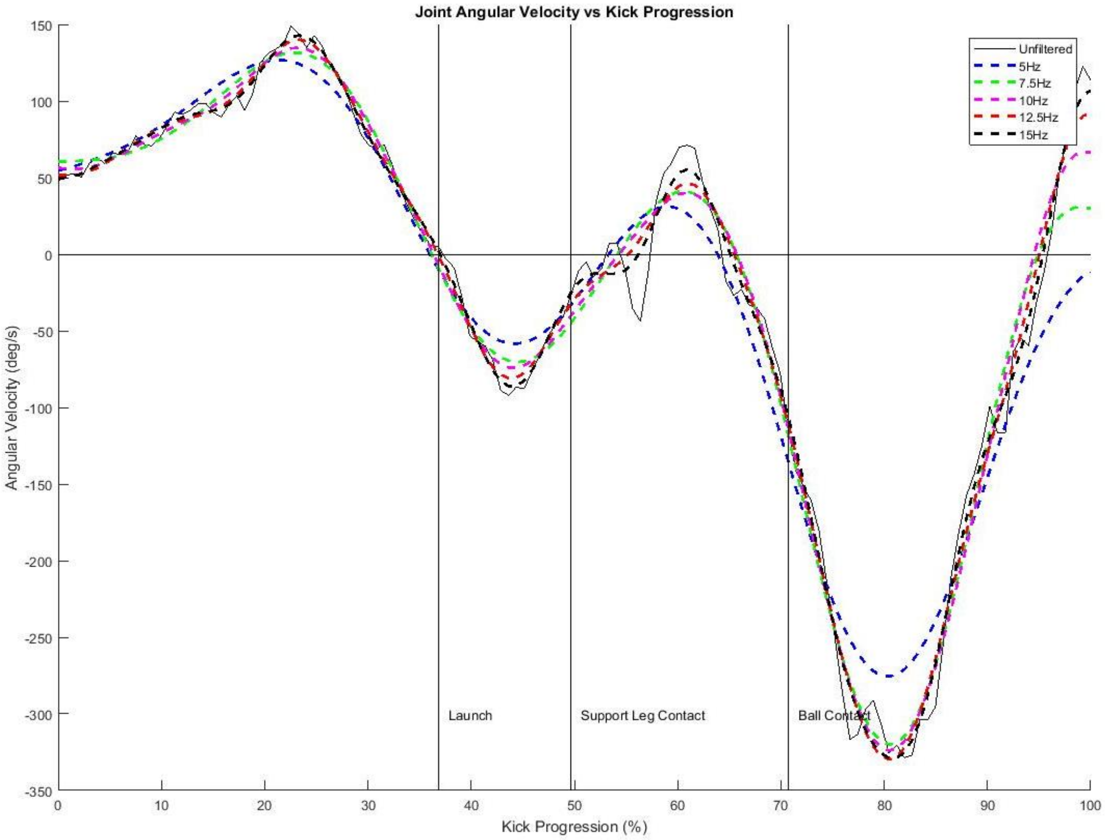

Figure 24: Thorax angular velocity during the rugby goal kick filtered at frequencies ranging from 5 to 15 Hz

Table 8 contains the magnitude of the peak angular velocities measured for the filtered thorax data. The table indicates a large variation in the magnitude of the velocity measured between different participants. The standard deviation for the peak velocities filtered at frequencies of 10 Hz, 12.5 Hz and 15 Hz are 72.70, 75.62 deg/s and 76.43 deg/s respectively. The deviation is as large as 50% of the mean velocity across all participants. In contrast to the large variation among the different participants, the difference between the peaks values filtered at various frequencies are very small. Contained in Table 9 are the variances in peak velocities caused by different filtering frequencies. It shows that the difference between the data filtered at 12.5 Hz and 15 Hz is as small as 4.99 deg/s (SD = 7.19), with the difference between the data filtered at 10 Hz and 12.5 Hz being only 7.94 deg/s (SD = 7.4). The relatively small velocity values may indicate that the thorax plays more of a supporting role during the kicking movement.

Table 8: Peak angular velocity of the thorax during a goal kick, filtered at frequencies ranging from 5 to 15 Hz

	Unfiltered	**5 Hz**	**7.5 Hz**	**10 Hz**	**12.5 Hz**	**15 Hz**
Mean	249.29	106.79	125.77	137.01	144.95	149.94
SD	161.80	51.80	64.61	72.70	75.62	76.43

Table 9: Variance in peak angular velocity of the thorax due to different filtering frequencies

	5 - 7.5 Hz	**7.5 - 10 Hz**	**10 - 12.5 Hz**	**12.5 - 15 Hz**
Mean	18.97	11.25	7.94	4.99
SD	37.82	17.03	7.40	7.19

4.2.4 Pelvis rotation

Similar to that of the thorax rotation, the pelvis is also susceptible to the effects of soft tissue artefacts and marker occlusion. This means that the pelvis rotation data is likely to contain spikes or discontinuities. Shown in Figure 25 is an example of pelvis rotation during a rugby goal kick. The data has been filtered at frequencies ranging from 5 to 15 Hz at intervals of 2.5 Hz. Similar to the thorax rotation, a negative angle indicates that the pelvis is rotated in a clockwise direction.

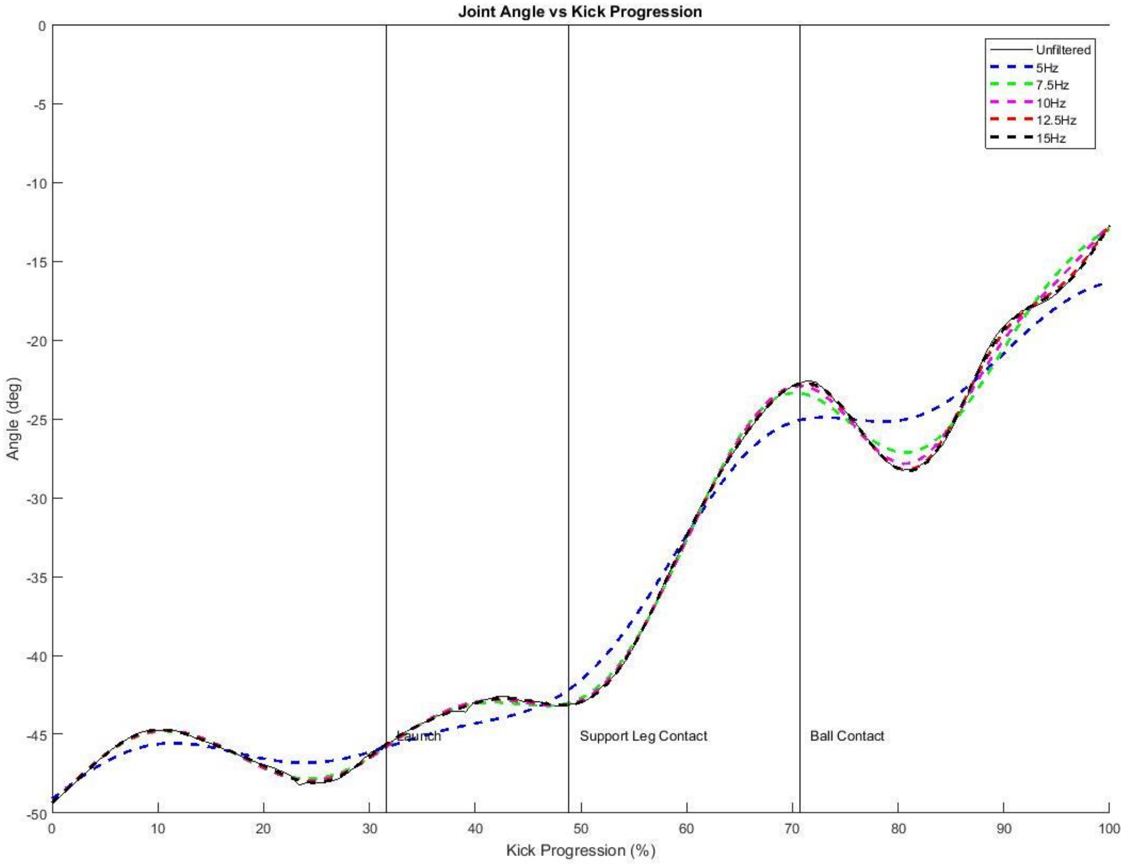

Figure 25: Pelvis rotation during the rugby goal kick, filtered at frequencies ranging from 5 to 15 Hz

In order to remove the angled approach of the participant, a fourth order high-pass Butterworth filter was applied with a cut-off frequency of 2 Hz. The resultant plot is shown in Figure 26. The plot shows the rotation of the pelvis about the direction the participant is moving. This view shows that the pelvis is relatively square at launch and is rotated in a counter-clockwise direction until the support foot is planted next to the tee. From this position the participant rapidly rotates the pelvis in a clockwise direction until contact is made with the ball.

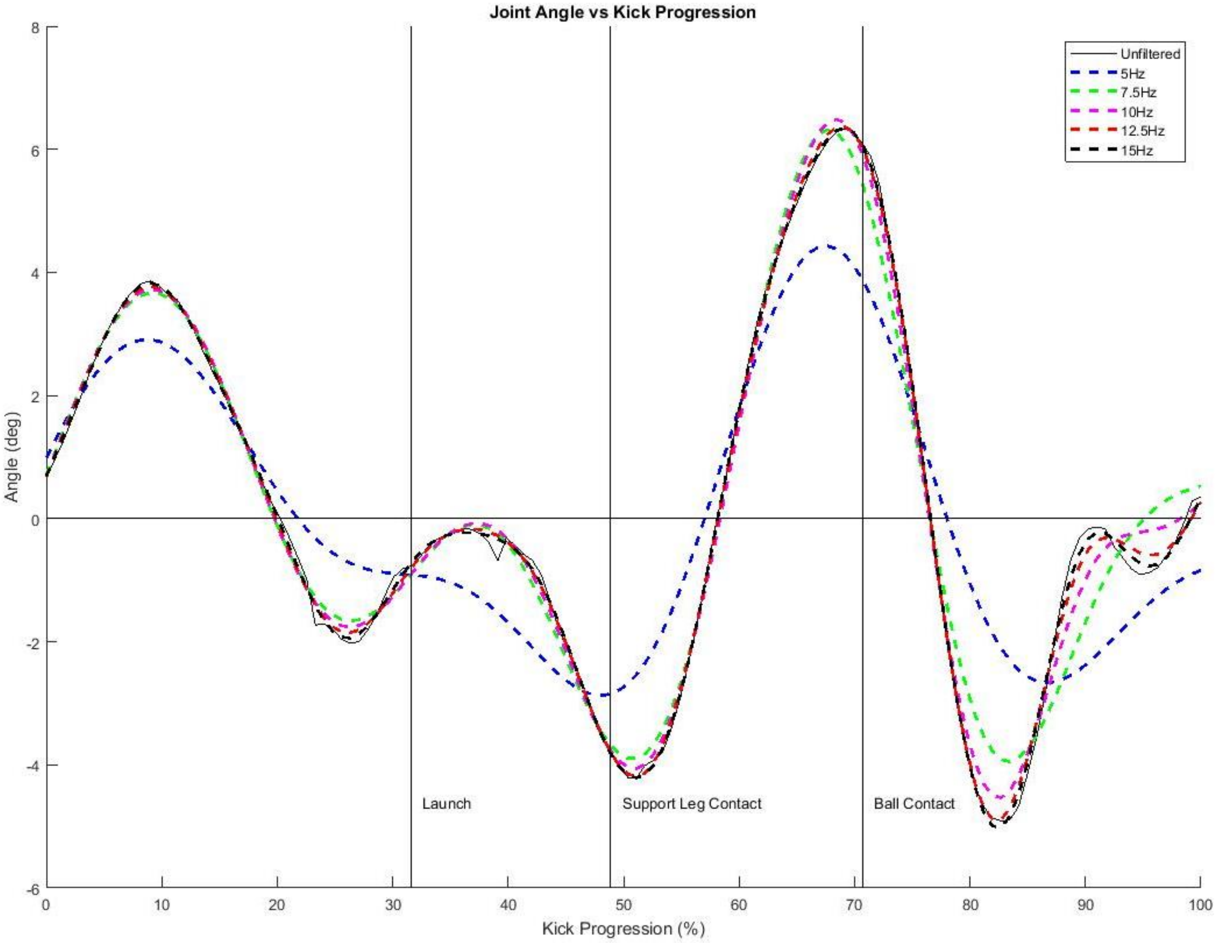

Figure 26: Pelvis rotation about the direction of travel during a rugby goal kick, filtered at frequencies ranging from 5 to 15 Hz

Figure 27 shows the time derivative of the pelvis rotation data in Figure 25. The effects of the various filtering frequencies on the angular velocity of the pelvis can clearly be observed. The peak velocity values seen in the figure is listed in Table 10. Although the differences in peak values caused by the different filtering frequencies are relatively small, there are large variations in magnitude between different participants. When considering the data filtered at a frequency of 10 Hz, the peak velocity ranges from 223 to 473 deg/s.

Table 10: Peak angular velocity of the pelvis during a goal kick, filtered at frequencies ranging from 5 to 15 Hz

	Unfiltered	5 Hz	7.5 Hz	10 Hz	12.5 Hz	15 Hz
Mean	374.82	221.20	324.59	357.29	361.88	363.99
SD	96.07	55.12	73.66	93.15	96.93	96.53

The difference in velocity between the different filtering frequencies is shown in Table 11. The peak velocity values are not greatly affected by the filtering process. The difference between the data filtered at 12.5 Hz and 15 Hz are only 2.1 deg/s (SD = 7.23) and the difference between the data filtered at 10 Hz and 12.5 Hz are 4.6 deg/s (SD = 13.58).

Table 11: Variance in peak angular velocity of the pelvis due to different filtering frequencies

	5 - 7.5 Hz	7.5 - 10 Hz	10 - 12.5 Hz	12.5 - 15 Hz
Mean	103.39	32.69	4.60	2.10
SD	37.94	29.65	13.58	7.23

When observing the angular data in Figure 25, it can be seen that the data filtered at 5 Hz greatly deviates from the general form of the unfiltered data. The data filtered at 7.5 Hz and to some extent the 10 Hz data, deviates to a much smaller degree than that the 5 Hz data, but it does seem to smoothen out the peaks in the data, reducing their peak values. This is likely an indication that the stricter filters are starting to attenuate a part of the actual signal. In Figure 27 the time derivatives of the data filtered at 12.5 Hz and 15 Hz are starting to be affected by the errors present within the data. It is therefore likely that these filters are failing to filter out the unwanted noise present in the data. This, coupled with the small change in peak velocity, leads to the assumption that the ideal cut-off frequency for the filtering the pelvis rotational data should be approximately 10 Hz.

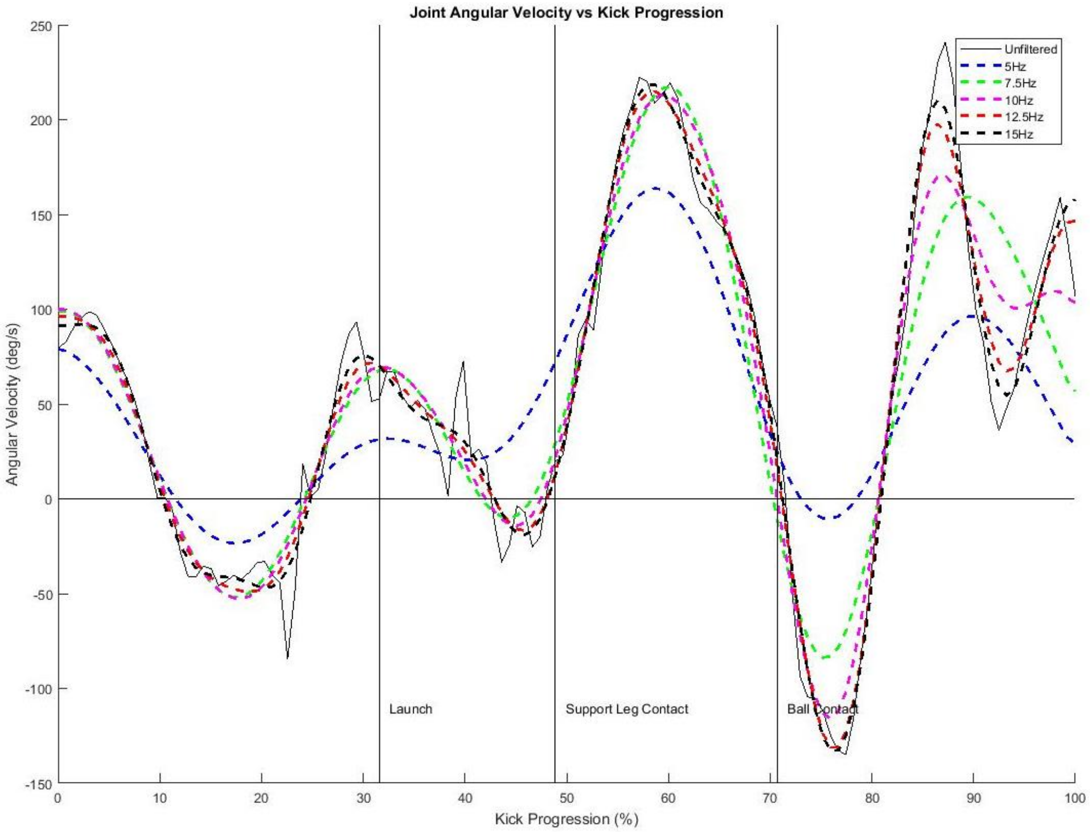

Figure 27: Pelvis joint angular velocity during the rugby goal kick filtered at frequencies ranging from 5 to 15 Hz

4.2.5 Whole Body Velocity

To mimic the movement of the entire body of a participant, the centre of the participant's pelvis is used as the 'root' of the body. The horizontal component of the positional data of this point is used to calculate the estimate whole body movement of each participant. Figure 28 shows an example plot of the velocity data of a participant during the kick. The positional data has been filtered at cut-off frequencies ranging from 5 to 15 Hz at intervals of 2.5 Hz. The effects of the different cut-off frequencies can be seen in Figure 28 It is evident that both the data filtered at 5 and 7.5 Hz tend to over smooth the data. As a conservative estimate the data was filtered at 10 Hz.

As seen in Figure 28, the velocity tends to flatten out just after the launch phase as the player is traveling through the air and has no control over the speed at which he travels. His velocity then starts to decrease as the supporting foot is planted next to the tee and the participant readies himself to make contact with the ball. Just prior to ball contact, the velocity tends to flatten again, as the leg is accelerated forward towards the ball.

Post ball contact the participant lifts of the ground as he hops forward, momentarily increasing the velocity again before coming to a standstill.

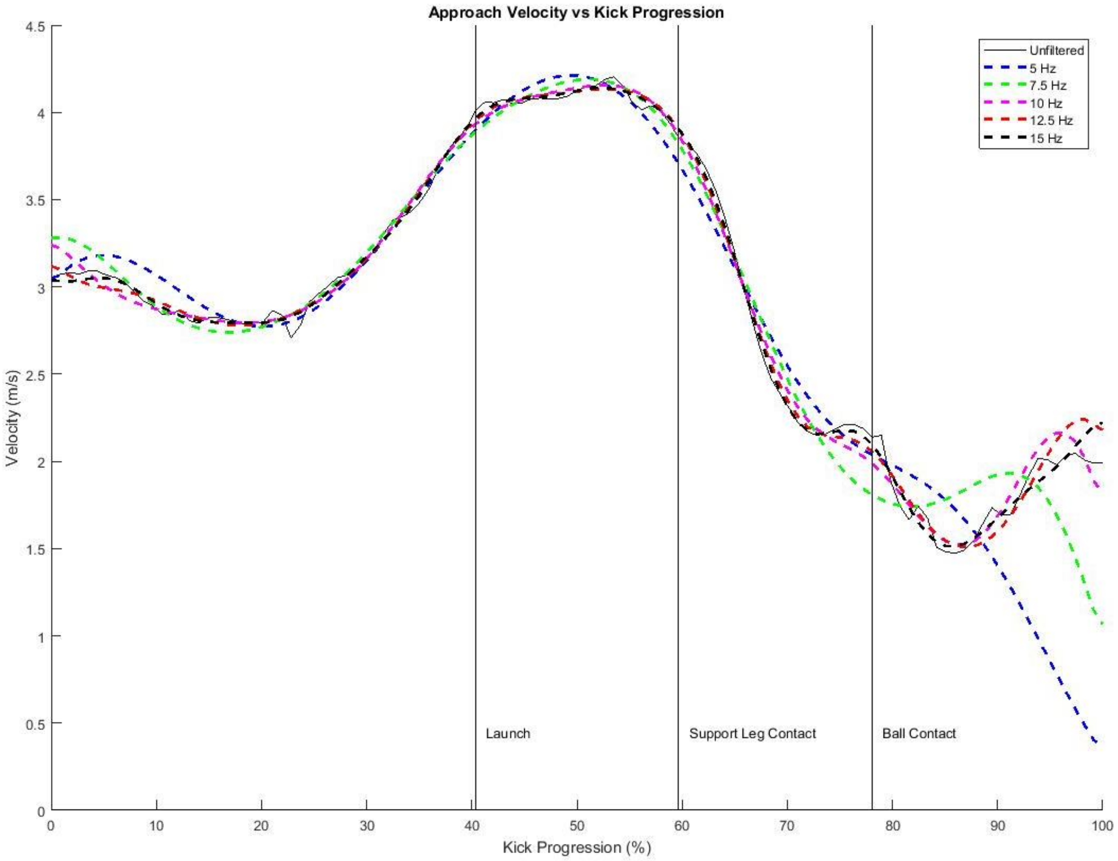

Figure 28: Whole body velocity during the rugby goal kick

The velocity of the body is of importance at two instances during the rugby goal kick. The first instance is the run-up or approach speed, which is estimated as the velocity of the body at the start of the launch phase, K2. The mean body velocity of the participants at this point is shown in Table 12. It shows that all the participants are very consistent in their approach speed, with Participant 5 having the largest standard deviation of only 0.14 m/s. The mean approach speed of all the recorded participants is 3.59 m/s (SD = 0.33), with values ranging from 3.06 to 4.02 m/s.

Table 12: Run-up/approach speed of the participants

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
Mean	3.95	3.06	3.97	3.52	3.80	3.79	3.30	3.42	4.02	3.11	3.46	3.69
SD	0.08	0.07	0.08	0.09	0.14	0.09	0.09	0.07	0.09	0.06	0.08	0.06

The second instance where the velocity of the body is of interest is at ball contact. This gives an indication of how much the participant is driving through the ball during the kick. The mean velocity of each of the recorded participants is shown in Table 13. The mean velocity at ball contact for all the participants is 1.69 m/s (SD = 0.34). The recorded values range from 1.24 m/s to 2.2 m/s. This shows that the participants still had a considerable amount of velocity as they kick the ball, indicating the participants do indeed attempt to kick through the ball as they do not stop before ball contact.

Table 13: Whole body velocity at ball contact

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
Mean	1.47	1.33	2.16	1.68	1.97	1.46	1.53	2.06	2.20	1.50	1.24	1.72
SD	0.16	0.06	0.08	0.10	0.10	0.28	0.11	0.08	0.12	0.09	0.09	0.10

4.2.6 Foot Speed

The speed at which the kicking foot is travelling is represented by the speed at which the toe marker on the kicking foot is travelling. To illustrate the importance and effect of proper filtering on the data set, the positional data of the three axes was filtered at intervals of 2.5 Hz, ranging from 5 to 15 Hz. The resultant graphs for one of the kicks are shown in Figure 29. It illustrates the effect that an interval of only 2.5 Hz has on the shape and peak values of the marker.

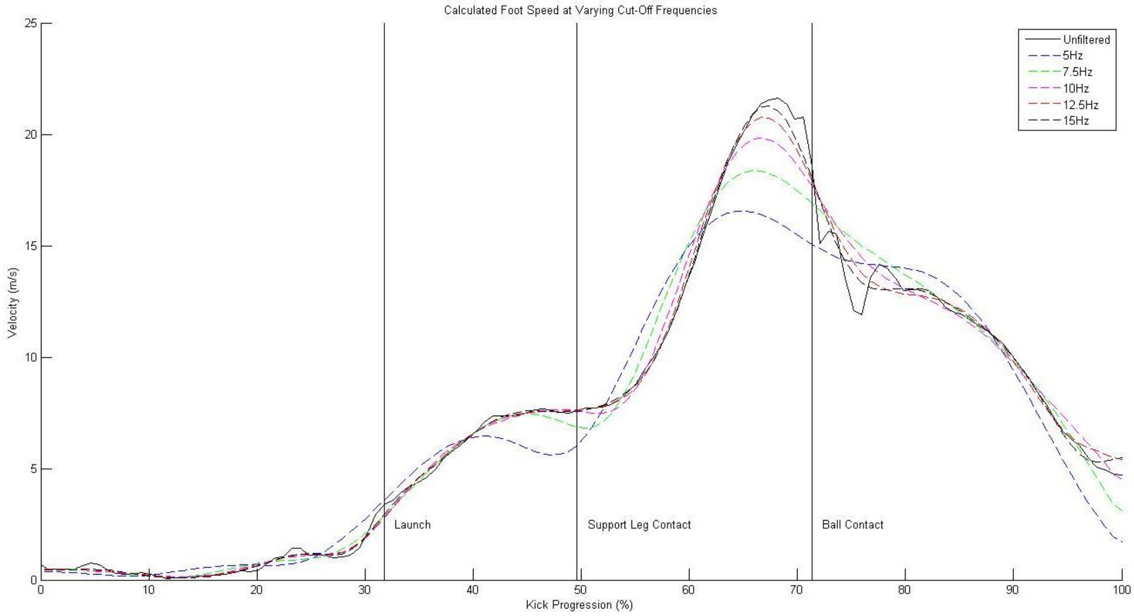

Figure 29: Foot velocity during the rugby goal kick, filtered at frequencies between 5 and 15 Hz, at intervals of 2.5 Hz

As seen in Figure 29, the unfiltered data of the foot speed shows a rapid decrease in foot speed around the ball contact, followed by some oscillation. This rapid change in velocity due to the impact with the ball occurs at a much higher frequency than the rest of the kick. Filtering both the low-frequency (swing phase) and high-frequency data (ball impact) together with a standard recursive Butterworth filtering approach is likely to distort kinematic information before and after impact (Knudson & Bahamonde, 2001). As the foot speed at ball contact is of greater importance than the general form during the earlier stages of the kick, it is decided that it would not be filtered.

Table 14 contains the mean calculated foot speeds for the different kickers. It shows the magnitude of the peak velocity for the data when the positional data is unfiltered. As the participants were instructed to kick towards an imaginary target that is a ‘midrange’ distance away, the amount of effort exerted during the kick was purely subjective. The magnitude of the foot speed does therefore not indicate the skill level of the kicker as it was not performed as a maximum effort kick. The mean unfiltered peak foot velocity calculated for the entire data set is 22.71 m/s (SD = 0.71). This is similar to the 21 m/s (SD = 1) reported by Ball, Talbert and Taylor (2013).

Table 14: Peak foot velocity (m/s) for all participants

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12

Mean	22.2	20.4	24.1	23.2	23.6	23.3	21.8	24.5	24.8	22.9	20.3	21.6
SD	0.35	0.42	0.21	1.61	0.32	0.22	0.20	0.43	3.67	0.18	0.82	0.30

4.2.7 Ball Velocity

As discussed in Chapter 2, ball speed and directionality are key performance indicators of a successful rugby goal kick. The entire purpose of the kicking process is to generate enough ball speed to enable the ball to travel the required distance to pass through the goal posts. The generation of ball speed should however not take complete preference over the control of the ball’s directionality. There is no purpose in being able to generate excessive amounts of ball speed, without being able to control the direction the ball travels.

During the flight of the ball, it tends to rotate due to its oval shape. In order to accurately tract the ball, the effect of the rotation must be cancelled out. This can be achieved by calculating the centre position of the ball. Three markers were placed on the ball; one on each side of the ball and one on the top. As the ball makes contact with the foot, there is a chance that one of the markers could fall off the ball. In such a case, the remaining two markers can be used to triangulate the position of the third marker, allowing for the calculation of the centre point of the ball.

As a check, ensuring that the one of the markers attached to the ball has not come loose during the kick, the distance between the two markers that are placed on the ball is calculated while the ball is stationary. The markers are placed on the midpoint of the ball at its widest diameter. The placement of the markers was however not always on the exact midpoint of the ball as the positioning of the markers were based on observation and were not accurately measured each time the markers were attached. The error caused by the marker placement, along with the diameter of the markers themselves, mean that the actual calculated distance is usually larger than the actual diameter of the ball itself. Figure 30 shows the dimensions of a standard rugby ball that is used in competitive matches. It indicates that the circumference of the ball is between 580 and 620 mm. This translates to a diameter of between 185 and 197 mm.

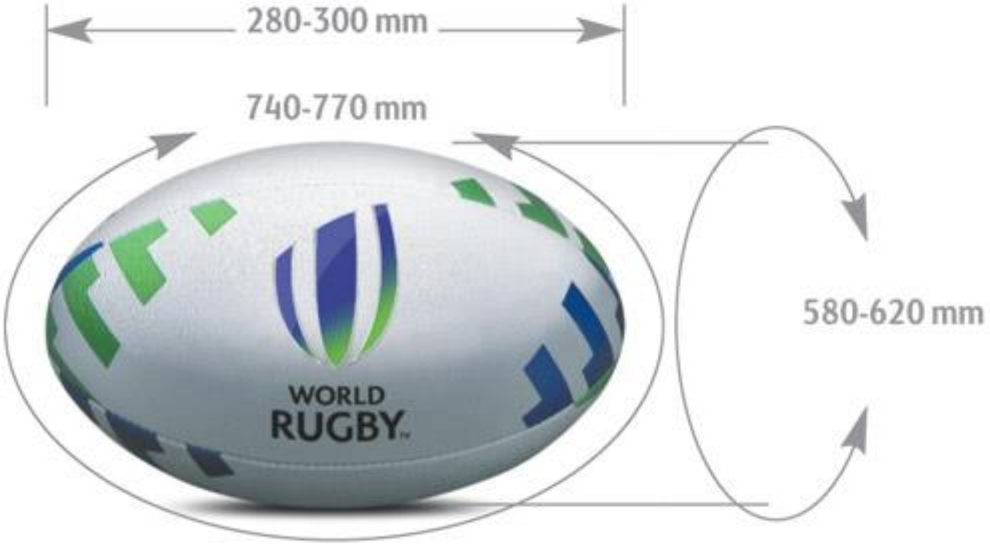

Figure 30: Dimension of a standard competition rugby ball *(World Rugby House, 2016, p. 31)*

The distance between the two markers placed on either side of the ball for each frame was compared to the stationary distances calculated and the error between the two values were used to determine whether the markers were still fixed to the ball. A threshold of 5% of the calculated distance was used to accommodate for measuring error or deformation of the ball during impact. In the case that the error becomes too large, it was deemed that the markers have separated from the ball and measurement of the ball kinematics is no longer possible.

Along with the possibility of the markers detaching from the ball during impact, the size of the capturing volume caused difficulty in the tracking of the ball. As the ball contact area is relatively close to the edge of the capturing volume and the rugby ball travels at high speeds, the number of usable frames for the tracking of the ball is very limited. Due to these difficulties in measuring, the ball speed for some of the kicks could not be calculated and will be omitted during the report of the results found.

The velocity of the ball is calculated by taking the time derivative of the positional data in each of the Cartesian axes. The magnitude of the velocity is determined by

$$V_m = \sqrt{V_x^2 + V_Y^2 + V_Z^2} \qquad (12)$$

with V_m being the magnitude and V_X, V_Y and V_Z being the calculated speeds in the three directions.

Due to the rapid change in position of the ball, it was decided that no filter would be applied to the positional data of the ball. Filtering, even at high frequencies, alters the measured kinematic data around the contact area. An example of the calculated velocity for the centre point of the ball is shown in Figure 31. It shows a rapid increase in velocity until it reaches its maximum. From there the velocity remains relatively constant, only decreasing slightly due to wind resistance. This rapid increase in velocity represents the impact period between the ball and the kicking foot. Once the foot loses contact with the ball, the velocity stagnates.

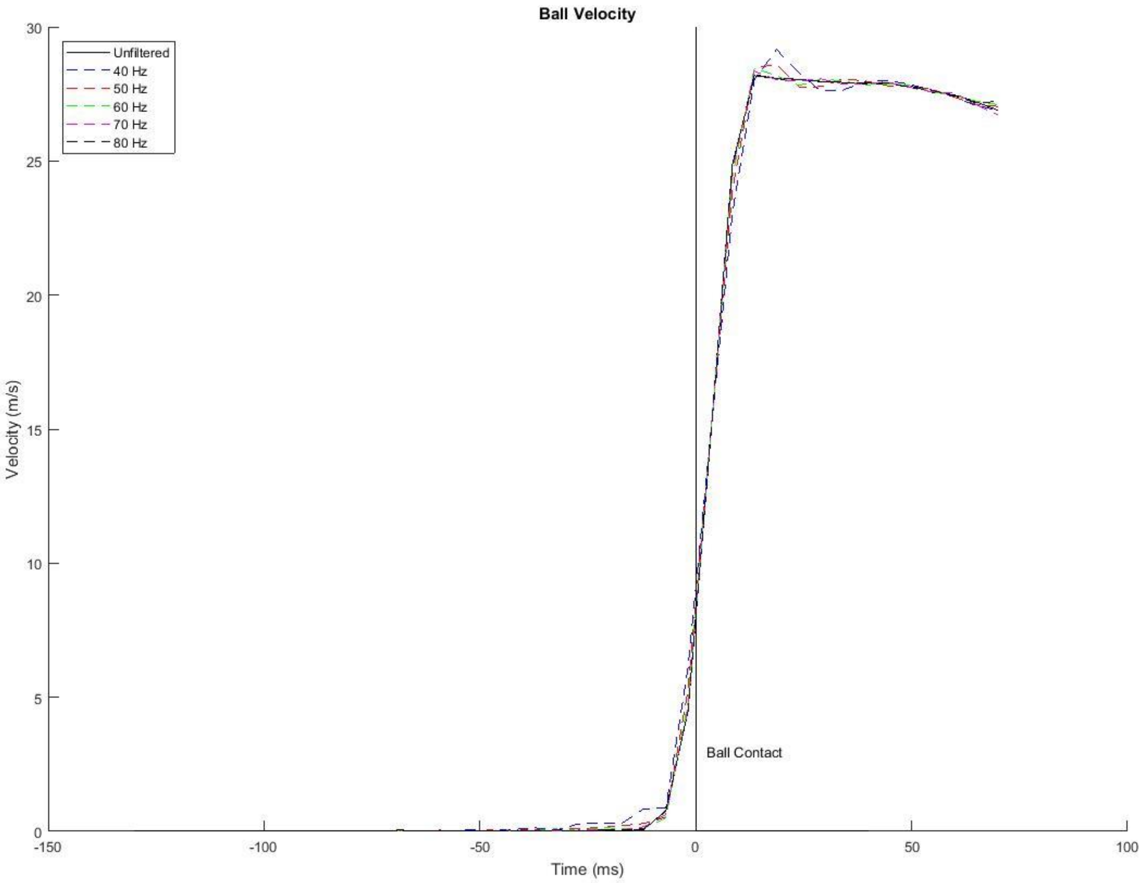

Figure 31: Ball velocity during ball contact

The peak velocity experienced by the ball post contact is shown in Table 15. The mean value, along with their standard deviation for each participant, is listed. Note that due to markers detaching from the ball or not enough frames being captured before the ball leaves the capture volume, the data does not include all of the captured kicks. For example, none of Participant 7's kicks allowed for the calculation of ball speeds.

Table 15: Peak ball velocity for each participant

	P1	P2	P3	P4	P5	P6	P8	P9	P10	P11	P12
Mean	27.74	25.32	30.88	28.05	27.77	27.83	28.78	27.91	28.07	27.14	28.15
SD	0.66	1.67	1.77	0.56	0.46	0.68	0.38	0.97	0.65	1.58	0.52

The participants were instructed to kick for a 'middle distance' kick and had no actual target to kick towards, meaning that the effort exerted for each kick was purely subjective. Even with this limitation, the recorded ball speeds for the participants are relatively consistent. The largest standard deviation amongst the participants was obtained from Participant 3, having a standard deviation of 1.77 m/s and a mean value of 30.88 m/s. The mean ball speeds found for the tested participants is 27.97 m/s (SD = 0.9).

Table 16 shows a comparison of the ball velocities calculated to the ball velocities reported on by several other related rugby goal kicking studies.

Table 16: Ball velocity (m/s) reported on by several rugby goal kicking studies

	Mean	SD
This study	27.97	0.9
Bezodis et al (2007)	24.54	0.98
Holmes et al (2006)	26.44	2.97
Ball et al (2013)	27	3

4.2.8 Launch Angle

Along with the velocity of the ball post contact, the angle at which the ball is launched determines the distance the ball will travel. Shown in Table 17 are the calculated angles for each of the participants. As discussed in Section 4.2.7 the markers on the ball were prone to detaching from the ball and the rapid change in the balls position resulted in it not always being possible to adequately track the ball for several of the kicks. Due to this, Participant 7 did not deliver any viable results.

Table 17: Launch angles (deg) for the participants

	P1	P2	P3	P4	P5	P6	P8	P9	P10	P11	P12
Mean	21.46	27.11	22.25	26.68	24.87	21.49	28.12	27.24	27.59	30.72	27.80
SD	1.57	1.65	1.51	0.90	1.85	2.26	1.10	2.21	1.37	0.79	2.21

The launch angle was calculated by tracking the positional data of the centre of the ball for several frames after contact. The angle between subsequent frames was calculated, as shown in Figure 32, and the mean of these angles was taken as the launch angle.

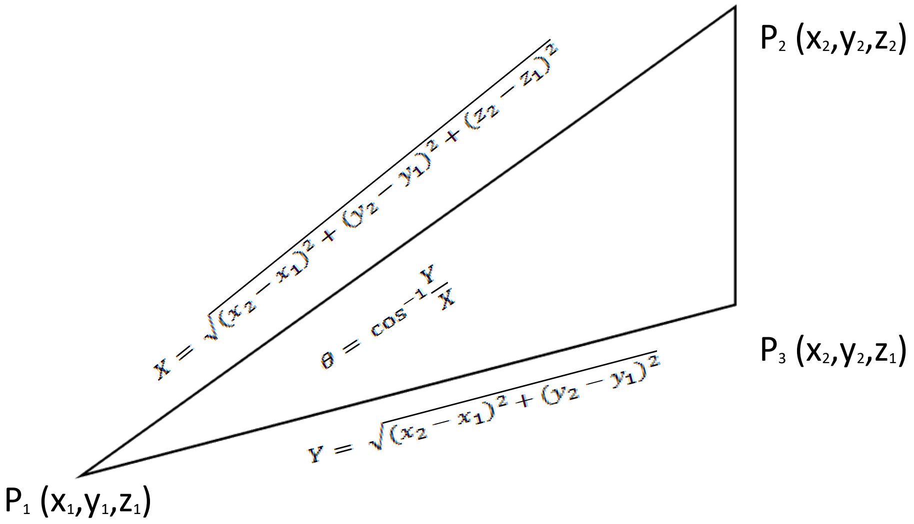

Figure 32: Illustration of method used to calculate elevation angle of the ball post ball contact.

In a study aimed at obtaining the optimal elevation angle for achieving maximum distance for rugby goal kicking, the ideal launch angle was determined as being in the range of 30° (Linthorne & Stokes, Optimum projection angle for attaining maximum distance in a rugby place kick., 2014). This is very similar to the mean launch angle of

30.22° (SD = 4.41) found by Holmes, Jones, Harland, and Petzing (2006). The mean angle found for the data set is 25.94° (SD = 1.58), which is slightly lower than the expected launch angle.

4.2.9 Transfer Efficiency

The Transfer Efficiency of the kick is defined as the ratio between the ball speed generated and the speed that the foot is traveling at ball contact. Table 18 shows the mean and standard deviation of the calculated Transfer Efficiencies for the participants. As discussed in the section on Ball Speed (Section 4.2.7), several of the recorded kicks do not have enough data to accurately track the ball kinematics. Due to this limitation, some of the kicks have been omitted in the calculation of the mean and standard deviation of the Transfer Efficiencies.

Table 18: Transfer efficiency for the participants

	P1	P2	P3	P4	P5	P6	P8	P9	P10	P11	P12
Mean	1.25	1.22	1.29	1.24	1.18	1.19	1.17	1.17	1.23	1.28	1.28
SD	0.02	0.05	0.07	0.03	0.02	0.02	0.02	0.03	0.02	0.02	0.01

The mean transfer efficiency calculated for the entire data set is 1.23 (SD = 0.03). This is in line with the values reported in another rugby goal kicking study, which reports values of between 1.2 and 1.3 (Ball, Talbert, & Taylor, 2013).

4.3 AUTOMATIC FILTERING ALGORITMS

The automatic filters tested in this study were Residual analysis, regression analysis and cumulative power analysis. The resultant cut-off frequency calculated for each of the implemented automatic filtering algorithms were captured in Table 19. The mean as well as the standard deviations of the calculated frequencies for the four joints are given. One of the biggest problems found with the filtering algorithms is their lack of consistency. As shown earlier in the chapter, the choice of cut-off frequency can greatly affect the data. The validity of the automatic filtering techniques is discussed in the sections to follow.

Table 19: Resultant cut-off frequencies (Hz) for the thorax rotation, pelvis rotation, hip flexion and knee flexion by the automatic filtering algorithms

Filtering Techniques	Thorax	Pelvis	Hip	Knee
Residual	18.03	19.18	23.02	24.03
	4.42	4.66	4.85	4.81
Regression	11.63	11.63	11.64	11.62
	2.06	2.05	2.05	2.06
Fourier 99%	25.30	17.72	49.55	11.80
	4.09	22.20	15.73	7.74
Fourier 95%	5.60	5.38	12.86	5.44
	0.90	13.42	5.44	3.34

4.3.1 Residual

The frequencies determined by following the guidelines laid out by Winter (2009) in the choice of cut off frequency in the residual analysis are all far higher than the ideal filtering frequencies hypothesised earlier in this chapter. This along with large variation in values calculated, rules out the use of this filtering technique for the context of the kinematic variables of a rugby goal kicking study. This method could however be explored further and a different means of choosing the cut-off frequency can be possibly be developed.

4.3.2 Regression

Regression analysis bases its initial estimate for the cut-off frequency on the sampling rate at which the data is recorded. From there, it adjusts the cut-off frequency based on the amount of error in the data. Most of the kicks were captured at a sampling rate of 200 Hz; however, there are several kicks that are captured at 400 Hz.

The cut-off frequencies calculated for the kicks that were sampled at 200 Hz are in the range of 11.2 Hz. In contrast the cut-off frequency for the kicks sampled at 400 Hz (20.5 Hz) is almost double that of the 200 Hz data. The frequencies calculated by the regression analysis are extremely consistent and the standard deviation found in Table 19 is caused by the few kicks that have been sampled at the higher sampling rate.

Based on the discussions of the influence that the filtering strictness have on the joint that are important for this study, the cut-off frequency found by the regression analysis can serve as a conservative implementation. It is however unknown whether it is by chance that the frequencies calculated are close to the hypothesized ideal values. In the case of the data captured at 400 Hz, the calculated cut-off frequencies are much higher than the estimated ideal frequencies.

Table 20 shows the initial cut-off frequency based on the sampling rate, as well as the revised cut-off frequency based on the residual between the unfiltered data and the data filtered at the initial cut-off frequency.

Table 20: Initial and revised cut-off frequencies (Hz) determined by regression analysis for sampling rates of 200 Hz and 400 Hz

	200 Hz	400 Hz
Initial cut-off frequency	13	23.6
Revised cut-off frequency	11.16	20.5

4.3.3 Cumulative Power Analysis (Fourier analysis)

The cumulative power analysis (Fourier analysis) calculates the cut-off frequency based on the frequency that a certain threshold of power contained in the signal is present in. The two thresholds that are commonly used are 95 % and 99 % of the accumulative power.

The largest concern with the Fourier analysis is around its consistency. As discussed earlier, the change in filtering frequencies greatly affects the shape of data. As seen in Table 19, the deviation in the cut-off frequencies calculated for the various parameters are extremely large, with the standard deviation of the pelvis cut-off frequency for the 99% energy content being as large as 22 Hz. The large variation in calculated values may be due to varying amounts of noise that are present in the different recorded kicks. As the cut-off is chosen based on the percentage of the total energy, the amounts of noise present in the signal, no matter at which frequency, increases the total energy of the signal. Meaning that two kicks can have exactly the same amount of energy present under a certain frequency, but the percentage represented at that frequency may greatly differ based on the higher frequency noise.

We know that there are high levels of noise and errors present around the ball contact area due to the contact between the foot and the ball. This noise is not present during the run-up and swing phase of the kicking movement. The higher frequency noise around the ball contact area therefore increases the total energy in the signal, increasing the calculated cut-off frequency. In an attempt to reduce the influence by the ball contact, the algorithm was applied to only the first part of the kick, up until ball contact. The resultant cut-off frequencies are shown in Table 21. It shows that the variability in the calculated frequencies is greatly reduced, especially for the 95% threshold. However even with the more consistent values, the values found for the different joints are generally either too strict or to lax.

Table 21: Cut-off frequency (Hz) determined using cumulative power analysis with ball contact excluded

Filtering Techniques	Thorax	Pelvis	Hip	Knee
Fourier 99%	26.90	14.10	40.15	10.87
	4.30	3.20	5.62	2.74
Fourier 95%	5.86	3.05	9.61	5.10
	0.98	0.46	1.78	0.48

4.4 BIOMECHANICAL ANALYSIS OF THE RUGBY GOAL KICK

The third part of the study involves establishing a biomechanical analysis of the rugby goal kick. The analysis involves plotting all the parameters crucial to the goal kick (thorax, hip etc) as percentage kick completed. Figure 33 demonstrates an example plot of the angular data of several joints of importance in the analysis of the rugby goal kick. The figure illustrates how the hip and knee is flexed after launch and how the hip reaches its maximum flexion at the same time that the support leg is planted next to the kicking tee. The knee continues to flex as the hip changes direction and starts to extend forwards. Only once the hip passes its neutral position does the knee change direction and rapidly extend towards ball contact. Just prior to ball contact the hip comes to almost a complete standstill and acts as a whip, accelerating the shank forward. The knee continues to extend past ball contact as it goes into slight hyperextension.

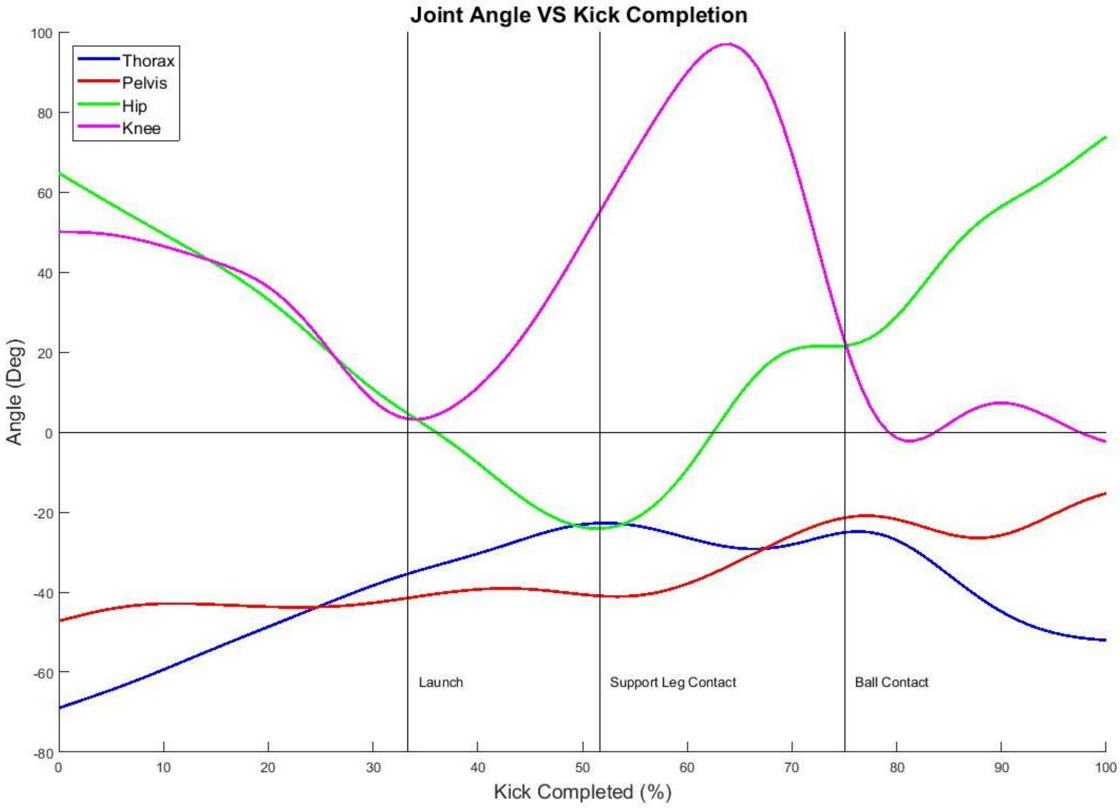

Figure 33: An example plot of all the joints of interest to a rugby goal kick

The movement of the pelvis is more difficult to visualise as the player approaches the tee from an angle. Figure 34 a) and b) illustrate the rotation of the pelvis and thorax during the kicking movement with their mean value removed. Meaning that the effects of the angled approach have been removed and the rotation about the direction of travel can be visualised. Both the thorax and pelvis possess very similar movements during the rugby goal kick. Both rotate clockwise during the flight phase; opening up the body as the support leg is planted next to the tee. An example of this 'open' position can be seen in Figure 35. This position allows the hip and knee to be moved through a large range of motion and allows the player to utilise a stretch reflex to accelerate the hip forwards. Shortly after the supporting foot makes contact with the ground and the hip starts to rotate forward, the pelvis and thorax rotate in a counter-clockwise direction aiding in generating foot speed.

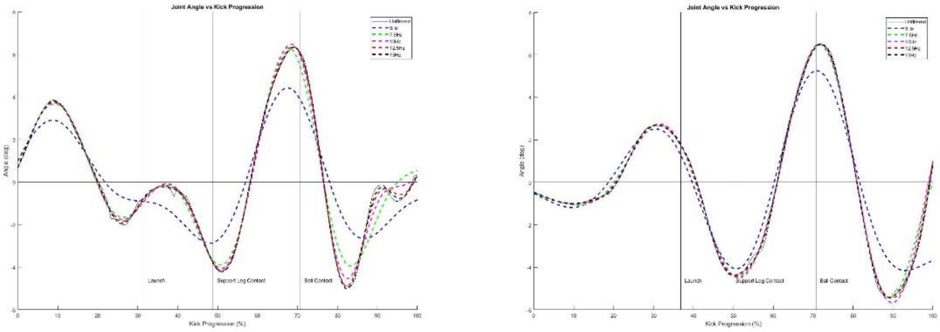

Figure 34: a) Pelvis and b) thorax angle around the direction of travel during a rugby goal kick

Figure 35: Kicker illustrating the 'open' body position just prior to the support leg contact (Retrieved online from http://www.sarugbymag.co.za/blog/details/lambie-retains-sharks-leadership-reins)

The maximum knee and hip flexion angles achieved by the various participants of the study are captured in Table 22. The knee flexion values range from 89.6 degrees up to 126.9 degrees. Hip flexion during the movement ranged from 16 degrees of flexion to 36.6 degrees of flexion. It is interesting to note that the participant what displayed the smallest range of motion in the knee flexion, also had the smallest hip flexion during the recorded kicks. Theoretically, a larger range of motion would allow for a longer distance to exert force upon, resulting in greater endpoint velocities. It is however unknown whether the participants with smaller flexion angles lack the required flexibility to achieve similar positions and/or whether there are other aspects that limit their movement. Apart from this, all the participants displayed very consistent flexion angles, having an average standard deviation of only 3 degrees for the knee flexion and 1.2 degrees for the hip flexion.

Table 22: Maximum knee flexion and hip extension during a rugby goal kick

Participants	Knee Flexion	Hip Flexion
P1	90.6	24.3
P2	89.6	16.0
P3	92.6	19.9
P4	109.7	22.6
P5	110.5	33.4
P6	101.9	28.6
P7	107.4	25.4
P8	105.2	36.6
P9	126.9	31.3
P10	123.7	26.7
P11	91.3	34.1
P12	89.8	22.9

Figure 36 shows the time derivatives of the example angular data shown in Figure 33 are illustrated in Figure 36. The figure illustrates how the peak foot velocity is reached at ball contact and how the different joints contribute to achieve this. As discussed in Chapter 2, the summation of speed principle states that the segment starts to accelerate forward as the previous segment in the chain reaches its peak velocity. This can easily be seen with regards to the hip and knee velocities during the rugby goal kick. Note that shortly after the hip reached its peak angular velocity, the knee changes direction and starts to rotate forward. From there, the hip velocity decreases, acting like the handle of a whip, accelerating the shank forward.

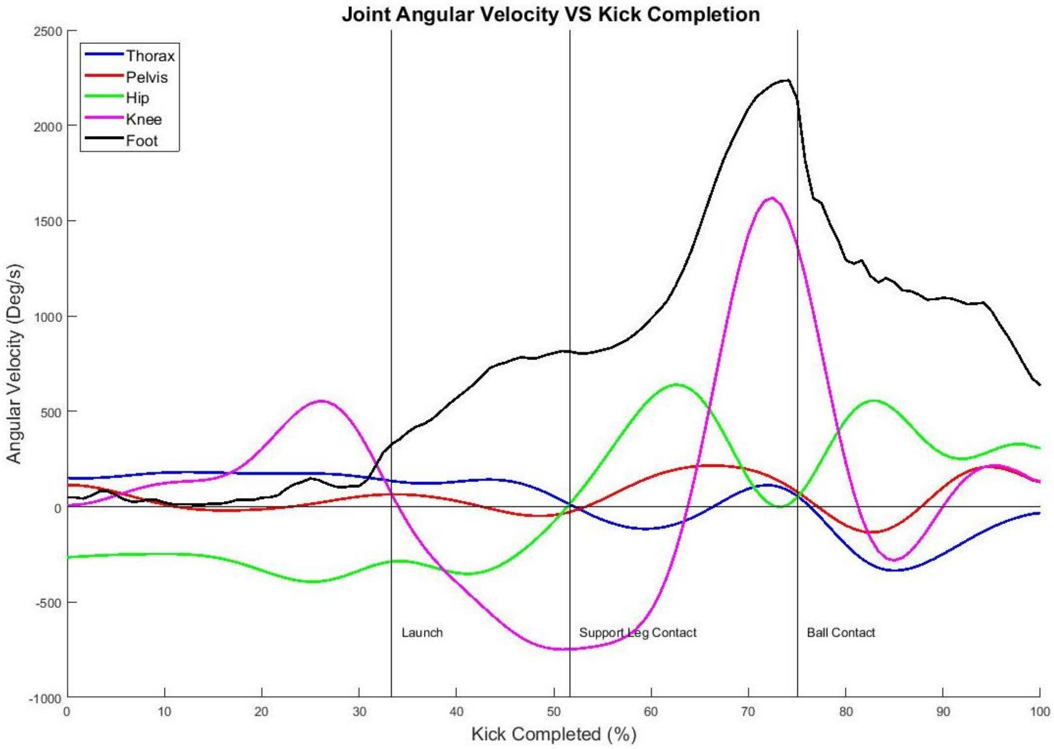

Figure 36: An example plot of the angular velocity for all the joints of interest to a rugby goal kick

In order to have a better understanding of the contribution of each of the joints during the goal kick, the peak angular velocity of each of the joints are analysed. The recorded peak velocity values for the joints and segments of importance to the explanation of the rugby goal kick are recorded in Table 23. Although the knee is the final joint in the kinematic chain and largely contributes to the generation of foot speed during the kick, there does not seem to be a simple relationship between the knee angular velocity and the foot speed generated.

Table 23: Peak knee, hip, pelvis, thorax and foot velocity values

	Peak Knee Velocity (deg/s)	Peak Hip Velocity (deg/s)	Peak Pelvis Velocity (deg/s)	Peak Thorax Velocity (deg/s)	Peak Foot Velocity (m/s)
P1	1514.07	538.46	223.97	93.72	22.15
P2	1411.58	510.67	280.80	28.39	20.42
P3	1572.62	496.46	473.37	129.50	24.07
P4	1848.51	537.43	442.65	13.63	23.24
P5	1874.64	684.72	457.66	165.94	23.58
P6	1582.66	452.44	382.41	74.88	23.28
P7	1812.59	529.73	276.19	80.23	21.82
P8	2013.73	693.05	283.57	78.03	24.50
P9	2127.11	516.56	470.75	26.44	23.58
P10	1971.99	708.78	434.55	249.24	22.86
P11	1435.82	568.71	261.27	262.38	18.52
P12	1464.77	431.63	317.07	47.85	20.58

Contained in Table 24 is the timing interaction between the peak velocities of the different joints. The timing difference is illustrated as the difference in the percentage of the completed kick. It can be seen that the knee consistently reaches its peak velocity value approximately 10 % later in the kick than the hip. This holds true for all of the participants tested. Similarly, the hip peaks on average 5 % earlier in the kicking movement than the pelvis. Although, the variance in timing between the hip and pelvis are larger than that of the hip and knee interaction, the pelvis reaches its peak value after the hip for every one of the recorded kicks. The timing of the thorax however is not as simple to analyse as the other joints. For the majority of the participants the thorax reaches its peak angular velocity very shortly after the pelvis and with high a high degree of consistency. The problem comes in the few outliers in the group of participants. For two of the participants the thorax reached its peak value more than 10 % earlier in the kicking movement than the pelvis. It is unknown whether this is caused by an error in the data processing procedure or whether the participants perform a different movement with their upper body.

If the two outliers are removed from the discussion regarding the thorax peak angular velocity, a clear pattern or sequence emerges. The summation of the foot speed is initiated by the large hip muscles, followed by the rotation of the pelvis and thorax and lastly the knee is rapidly extended.

Table 24: Difference in timing of peak joint velocities, illustrated in percentage of the completed kick

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
Hip - Knee	9%	10%	12%	12%	10%	10%	10%	11%	12%	11%	8%	10%
Pelvis - Hip	-2%	-4%	-7%	-7%	-6%	-5%	-6%	-4%	-7%	-7%	-5%	-4%
Thorax - Pelvis	-6%	1%	-4%	12%	-4%	-2%	-2%	-5%	13%	-2%	-2%	-1%

As discussed earlier in both this section and in more detail in Chapter 2, the rugby goal kick consists of several key events. Contained in Table 25 are the timing differences between these events for the tested participants. The average duration of the performed kicks from either S1 or K1 (depending on which occurs first) to S3 was 0.64 s. The largest amount of variance amongst the different participants is present during the last preparatory step before the flight phase and during the follow-through phase post ball contact. Although there is some variance between the different participants, the individual participants displayed extremely consistent kicking phase times. This can be illustrated by the fact that the average standard deviation of the percentage the different events occurred at during the kick is only 1%.

Table 25: The timing difference between events (s)

	S1/K1 to K2	K2 to S2	S2 to K3	K3 to S3	Whole Kick
Mean (s)	0.229	0.121	0.128	0.162	0.640
SD (s)	0.031	0.021	0.015	0.025	0.04

Another aspect of the kick was the high levels of consistency showed by the participants in the distance of the final stride (distance between kicking foot at K2 and non-kicking side foot at S2) during the flight phase. The recorded values for each of the participants are given in Table 26. The data shows that over an average of 1.55 m, the average standard deviation is only 24 cm. In contrast to these low amounts of deviation found for each kicker, the distances achieved largely differs between participants. In order to try to explain the reason for the varying distances, the distances were compared to the speed at which the participant was traveling just prior to initiating the final stride. A regression line correlating the distance length of the stride the speed of the body was constructed (see Figure 37).

Table 26: Length of the final step before ball contact (m)

	Mean	SD

	(m)	(m)
P1	1.74	0.03
P2	1.37	0.04
P3	1.56	0.03
P4	1.40	0.02
P5	1.60	0.04
P6	1.86	0.03
P7	1.49	0.04
P8	1.50	0.03
P9	1.51	0.03
P10	1.50	0.03
P11	1.52	0.02
P12	1.59	0.02
Mean	1.55	0.02

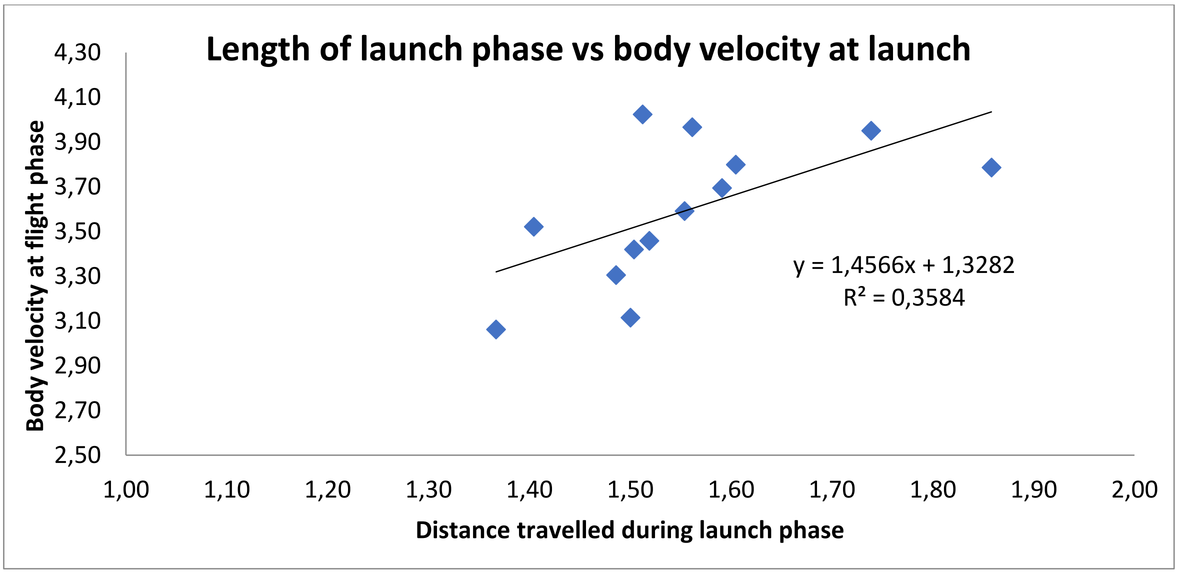

Figure 37: Regression analysis between the distance travelled during the flight phase and the speed at which the body was moving just prior to launch.

The coefficient of determination (R^2) reported for the relationship between the two variables is rather weak, being only 0.36. The implication is that although the one is affected by the other, the speed of the body does not fully explain the distance travelled.

4.5 CHAPTER CONCLUSION

In this chapter the effects of the choice in filtering frequency was presented and discussed. The ideal filtering parameters were obtained for various kinematic parameters. The validity of several automatic algorithms was tested. This was followed by the presentation and discussion of the results of the biomechanical analysis of the rugby goal kicking kinematic data. The chapter is concluded with the identification of a possible kinetic sequence. The study is concluded in the chapter to follow.

CHAPTER FIVE

CONCLUSION

5.1 INTRODUCTION

This study set out to develop a knowledge base around the biomechanical processing and analysis of the rugby goal kick. The following three objectives were formulated: determining the ideal filtering parameter for use on rugby goal kicking kinematic data, the testing of possible automatic filtering algorithms and to identify the kinematic sequences by means of a processing tool.

In the sections to follow, the outcomes of these objectives are discussed, in addition to a discussion around the limitations of the study and recommendations for further research.

5.2 THE IDEAL FILTERING PARAMETERS FOR RUGBY GOAL KICKING KINEMATIC DATA

Although there are some variances between the recorded kickers, it was determined that a general conservative estimate for the filtering of joint kinematics for a rugby goal kick is approximately 10 Hz. This holds true for the filtering of the pelvis and pelvis rotation, as well as the flexion/extension of the hip and knee. It was found that filtering at frequencies lower than 10 Hz generally resulted in the shape of the angular data being altered. As the levels of low frequency noise present in the angular data are relatively low, it is assumed that the general form of the unfiltered angular data matches that of the true signal. If the filtering process therefore greatly alters the shape of the angular data, it is likely that it is starting to attenuate the signal itself and is deemed to be too strict.

During the derivation process, the effects of the high frequency noise are amplified greatly. The noise that had little to no effect on the angular or positional data can become prominent in the velocity data. This causes spikes or discontinuities in the data to become prominent. Via inspection of the velocity data of several of the joints, it was determined that the data filtered at 15 Hz and in some cases 12.5 Hz, are likely to follow these spikes in the data. As it is known that these spikes are noise contained in the data, their effects should be removed. Therefore, filtering at these frequencies (12.5 Hz and 15 Hz) is allowing some the noise to remain in the data. The data filtered at 10 Hz was found to be a conservative middle, not largely differing from the angular data and not greatly being affected by the noisy spikes in the velocity data.

5.3 VALIDITY OF AUTOMATIC FILTERING ALGORITHMS

None of the automatic filtering algorithms that were tested produced satisfactory results. The cut-off frequencies determined using the residual analysis and cumulative power analysis methods displayed extremely large variance in the values calculated. The average frequencies determined by the residual analysis were much larger than the theoretical ideal cut-off frequencies determined through visual inspection. Due to the above results, neither residual nor cumulative power methods are recommended for the use in goal kicking studies. Cut-off frequencies calculated by regression analysis are much closer to that of the theoretical ideal cut-off frequencies determined in prior studies. However, it is unclear whether this was purely by chance as only the data that were sampled at a frequency of 200 Hz resulted in a useable cut-off frequency. In the case of the data that was sampled at the higher frequency of 400 Hz, the cut-off frequency was much larger that the theoretical ideal value.

Based on the analysis of the effects that the choice in cut-off frequency has on the validity of the different data sets of interest in this rugby goal kicking study, the use of the above mentioned automatic filtering algorithms are not recommended.

5.4 KICKING BIOMECHANICS

One prominent aspect stood out during the analysis of the group of participants, namely the consistency at which the movements were repeated. The variance between timing events for each individual kicker was extremely small and certain key events during the movement were performed time and time again at the exact position in the kick. It is unknown whether the repeatability of kicks is what defines the participants tested as elites, and therefore the variability in results should be classified as an important aspect of a successful kicker.

5.5 KINEMATIC SEQUENCE OF A RUGBY GOAL KICK

Apart from two outliers in the data set, a definitive sequence of joint interactions was present during the rugby goal kicking movement. It was found that during the goal kick, the movement is initiated by the large hip joint and they reach their peak velocity first, followed by the pelvis, shortly thereafter the thorax and lastly the knee reaches its peak angular velocity as the last major joint before the endpoint. All four joints therefore work in unison to ultimately generate as much foot speed as possible during the kicking movement.

5.6 LIMITATIONS

This study forms part of a bigger project and made use of data collected as part of the bigger project, which resulted in some data limitations for the context of this study. Due to the rigorous schedule of the professional players that participated in the study, as well as the fact that they were based around the entire country, the testing had to be completed within a short time frame. As a result of the time frame limitations, some cases of marker exclusion were encountered, resulting in several of the recorded kicks not to be considered for this study.

At the time of testing, the equipment required to perform motion capturing outdoors were not available to the motion analysis laboratory of Stellenbosch University. This limited the capturing of data to an indoor laboratory. Indoor capturing of rugby goal kicking is not ideal as it does not accurately mimic the circumstances actual goal kicks are attempted under. During a match setting, goal kicks are attempted on grass, wearing rugby boots and the goal posts serve as a visual target for players to judge the required distance and angle the kick must be completed for. However, in the laboratory the kicks were completed on hard rubber flooring, wearing running shoes and kicking the ball into a net. The distance required for a successful kick was based on the personal perceptions of the participants in this unnatural environment.

5.7 RECOMMENDATIONS FOR FUTURE RESEARCH

As this study forms part of a larger and on-going project to broaden the scientific knowledge surrounding the rugby goal kick, the shortcomings, errors and findings that are discovered during this study will be used to further improve the means by which rugby goal kicking data is recorded and processed in future.

The first aspect that requires improvement is the means by which the markers have been placed on the thigh of the participants. During inspection of high speed footage of the recording process, large amounts of deformation of the thigh is visible. The location of the thigh marker plays a large role in the calculation of both the hip and knee angle and due to the high frequency nature of the ball contact it is extremely difficult to discern the effects of the error from the effects of the contact with the ball. The problem may be alleviated by implementing a different marker placing scheme; one that incorporate additional marker clusters.

In addition, it would be recommended to capture the kinematics around the ball contact area at much higher sampling rates. In a study investigating the impact phase kinematics during a soccer kick (Nunome, Lake, Georgakis, & Stergioulas, 2006), it was found that the contact phase of a kick should ideally be captured at sampling rates in excess of 1000 Hz. Coupled with the higher sampling rates, a time varying frequency filtering algorithm is recommended, capable of filtering a signal at various frequencies throughout the signal. This would allow for a different filtering frequency during the contact phase than during the lower frequency swing phase of the kick.

Along with the above-mentioned recommendations, the next phase in testing would be to conduct tests that are performed outdoors. This would allow the participants to perform the kicks on grass, wearing their rugby boots that have been designed specifically for the use in goal kicking. The mental state of players will also be altered, as they will have a visual target that is a visible distance away from the tee. It will furthermore improve tracking of the quality of the kicks that have been performed; the only available means of determining the quality of a kick in the indoor setting was via the subjective rating of the participant. The rating was purely based on how the participant perceives their kick, and as the conditions are so far removed from the conditions participants are accustomed to, they are not an ideal indication of the quality.

5.8 CONCLUSION

The most tangible deliverables of this study are the identification of a definite kinetic sequence during the rugby goal kick, as well as being able to determine the ideal filtering frequencies for kinematic variables of importance to the study of the rugby goal kick. Another contribution of the study is the realisation that the automatic filtering algorithms applied did not result in adequate filtering parameters. It is hoped that this study, along with its future phases as envisaged in the larger research project discussed in Chapter 1, might contribute to the development of the knowledge base for rugby.

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APPENDIX A: Participant Data

The data for each of the twelve participants are provided below. The data consists of a set of graphs depicting the joint kinematics, accompanied by a set of five tables for each participant. The general structure of the data report is illustrated below.

Figure A1: Joint kinematics of participants

Table A1: Peak velocities, along with the position at which they occur

Table A2: The timing of the different phases present in a rugby goal kick

Table A3: The key events during the goal kick

Table A4: The length of the final stride before ball contact

Table A5: The magnitude and position of maximum knee and hip flexion

Participant 1

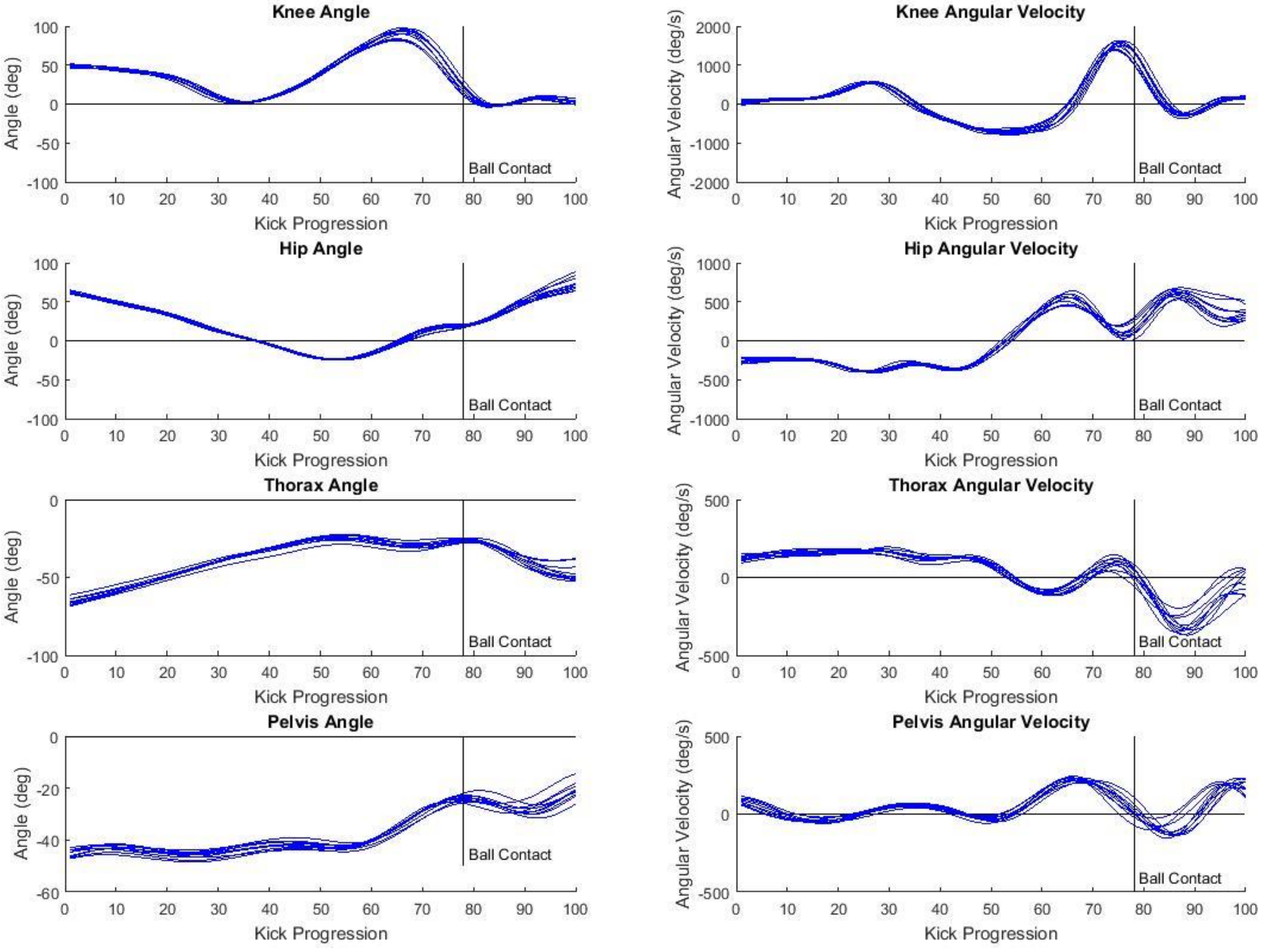

Figure A1: Joint kinematics of Participant 1

Table A1: Peak velocities, along with the position at which they occur (Participant 1)

		K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
Knee	Peak Velocity (°/s)	1569.4	1509.6	1418.6	1372.8	1619.5	1380.3	1557.2	1598.0	1630.8	1484.3	1514.1	91.97
	Peak Velocity Position	67%	73%	69%	68%	73%	70%	66%	71%	70%	73%	70%	2%
	Peak to BC (s)	0.220	0.170	0.200	0.210	0.165	0.180	0.220	0.175	0.185	0.170	0.190	0.020
Hip	Peak Velocity (°/s)	561.44	601.34	448.83	465.85	639.91	457.36	551.10	552.12	599.00	507.65	538.46	62.94
	Peak Velocity Position	59%	63%	61%	59%	63%	61%	57%	62%	61%	63%	61%	2%
	Peak to BC (s)	0.275	0.230	0.255	0.265	0.225	0.235	0.280	0.230	0.240	0.230	0.247	0.020
Pelvis	Peak Velocity (°/s)	213.05	199.94	235.94	229.69	215.55	243.12	216.88	227.05	230.19	228.32	223.97	11.95
	Peak Velocity Position	60%	65%	62%	60%	67%	62%	59%	63%	65%	65%	63%	3%
	Peak to BC (s)	0.270	0.215	0.250	0.260	0.200	0.230	0.265	0.225	0.220	0.220	0.236	0.023
Thorax	Peak Velocity (°/s)	92.14	98.31	43.56	81.15	112.79	43.90	145.41	82.16	124.89	112.85	93.72	31.12
	Peak Velocity Position	66%	73%	69%	67%	72%	68%	65%	71%	70%	72%	69%	3%
	Peak to BC (s)	0.225	0.170	0.205	0.215	0.170	0.195	0.230	0.175	0.185	0.175	0.195	0.022
Foot	Peak Velocity (m/s)	21.94	22.24	21.69	21.62	22.36	22.52	22.13	22.55	22.53	21.93	22.15	0.33
	Peak Velocity Position	68%	73%	70%	68%	74%	72%	67%	73%	73%	75%	71%	3%
	Peak to BC (s)	0.215	0.165	0.195	0.205	0.155	0.170	0.215	0.165	0.170	0.160	0.182	0.022

Table A2: The timing of the different phases present in a rugby goal kick (Participant 1)

	K1	**K2**	**K3**	**K4**	**K5**	**K6**	**K7**	**K8**	**K9**	**K10**	**Mean**	**STD**
S1/K1 to K2	0.210	0.205	0.210	0.205	0.200	0.190	0.180	0.185	0.190	0.205	0.198	0.011
K2 to S2	0.115	0.125	0.130	0.115	0.110	0.130	0.125	0.125	0.130	0.140	0.125	0.009
S2 to K3	0.145	0.135	0.135	0.140	0.140	0.130	0.140	0.135	0.135	0.135	0.137	0.004

K3 to S3	0.200	0.155	0.180	0.190	0.155	0.160	0.205	0.160	0.165	0.150	0.172	0.020
Whole Kick	0.67	0.62	0.655	0.65	0.605	0.61	0.65	0.605	0.62	0.63	0.632	0.023

Table A3: The key events during the goal kick (participant 1)

	K1	**K2**	**K3**	**K4**	**K5**	**K6**	**K7**	**K8**	**K9**	**K10**	**Mean**	**STD**
S1/K1	0	0	0	0	0	0	0	0	0	0	0%	0%
K2	31%	33%	32%	32%	33%	31%	28%	31%	31%	33%	31%	2%
S2	49%	53%	52%	49%	51%	52%	47%	51%	52%	55%	51%	2%
K3	70%	75%	73%	71%	74%	74%	68%	74%	73%	76%	73%	2%
S3	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	0%

Table A4: The length of the final stride before ball contact (participant 1)

	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
Distance of Launch (m)	1.701	1.755	1.735	1.762	1.741	1.771	1.705	1.760	1.762	1.700	1.739	0.026

Table A5: The magnitude and position of maximum knee and hip flexion (participant 1)

		K1	**K2**	**K3**	**K4**	**K5**	**K6**	**K7**	**K8**	**K9**	**K10**	**Mean**	**STD**
Max Knee Flexion	Angle	94.00	90.34	82.64	81.46	96.90	83.73	93.55	94.90	97.68	90.33	90.55	5.68
	Position	59%	65%	61%	59%	64%	61%	58%	63%	62%	64%	62%	2%
Max Hip Flexion	Angle	-23.76	-24.64	-23.20	-24.87	-24.12	-24.40	-24.76	-25.14	-24.64	-23.81	-24.33	0.57
	Position	49%	52%	51%	49%	52%	50%	47%	50%	50%	52%	50%	2%

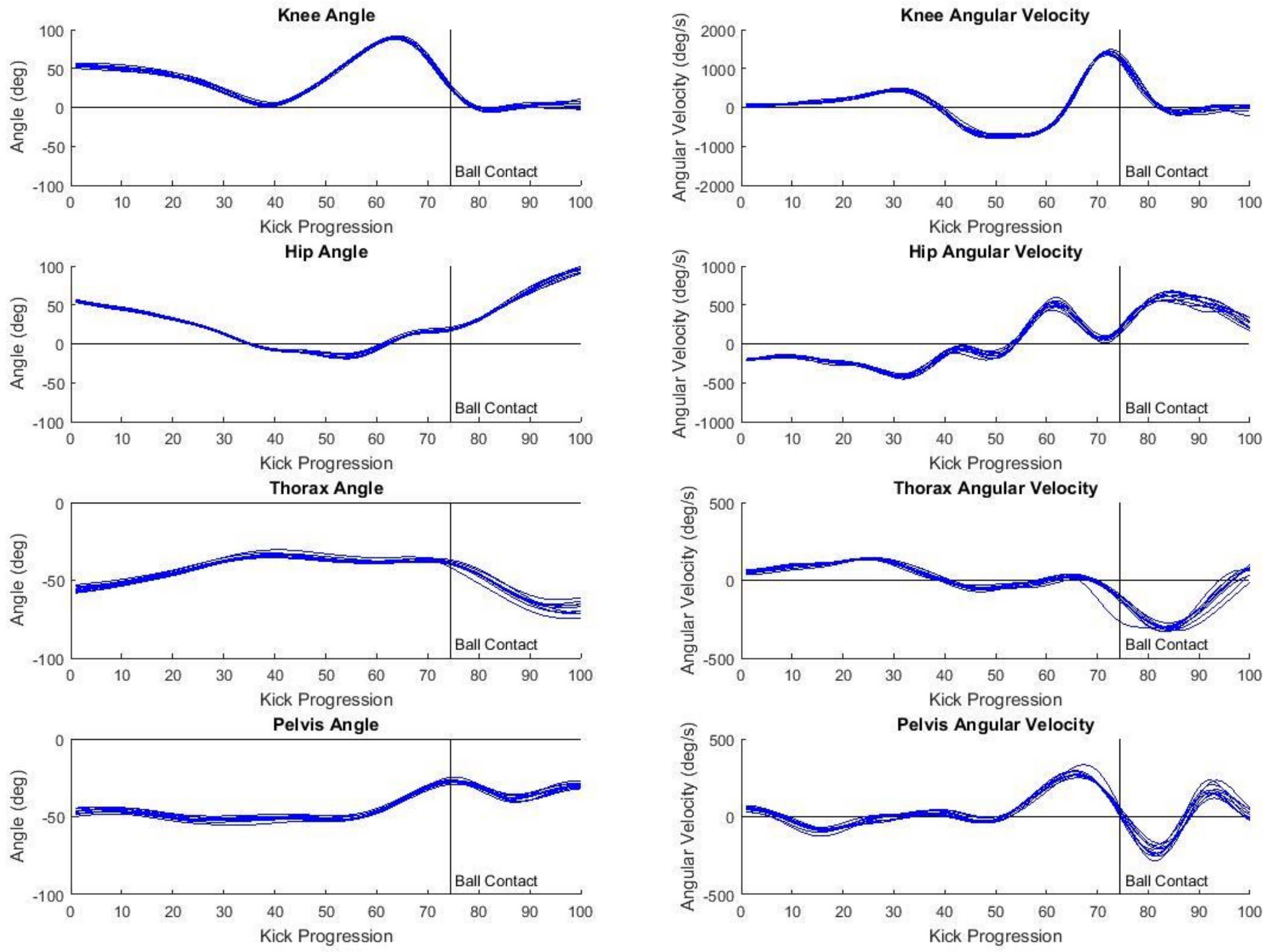

Figure A2: Joint kinematics of Participant 2

Participant 2

Table A6: Peak velocities, along with the position at which they occur (Participant 2)

		K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
Knee	Peak Velocity (°/s)	1412.96	1492.51	1425.67	1338.91	1386.15	1374.40	1394.54	1457.15	1393.41	1440.10	1411.58	41.92
	Peak Velocity Position	67%	73%	69%	70%	69%	69%	69%	71%	70%	72%	70%	2%
	Peak to BC (s)	0.225	0.170	0.210	0.195	0.210	0.200	0.205	0.185	0.190	0.180	0.197	0.016
Hip	Peak Velocity (°/s)	430.65	594.46	469.08	493.89	501.53	479.59	516.04	539.45	554.63	527.35	510.67	44.22
	Peak Velocity Position	57%	62%	58%	60%	59%	59%	59%	61%	60%	61%	60%	1%
	Peak to BC (s)	0.295	0.240	0.280	0.260	0.275	0.265	0.270	0.250	0.255	0.250	0.264	0.016

	Peak Velocity (°/s)	293.03	333.66	264.14	266.93	250.14	296.07	292.17	267.64	271.65	272.56	280.80	22.45
	Peak Velocity Position	60%	68%	62%	64%	63%	64%	63%	65%	65%	65%	64%	2%
Pelvis	Peak to BC (s)	0.270	0.205	0.255	0.235	0.245	0.235	0.245	0.225	0.225	0.225	0.237	0.017
	Peak Velocity (°/s)	19.03	28.58	40.06	21.00	35.81	38.63	10.40	27.96	24.01	38.39	28.39	9.39
	Peak Velocity Position	60%	67%	61%	63%	61%	63%	64%	64%	63%	64%	63%	2%
Thorax	Peak to BC (s)	0.270	0.210	0.260	0.240	0.260	0.240	0.240	0.230	0.240	0.230	0.242	0.017
	Peak Velocity (m/s)	20.16	21.12	20.60	20.48	19.61	20.08	20.87	20.47	20.33	20.53	20.42	0.40
	Peak Velocity Position	67%	73%	69%	70%	69%	70%	69%	71%	71%	72%	70%	2%
Foot	Peak to BC (s)	0.225	0.170	0.210	0.195	0.205	0.195	0.205	0.185	0.185	0.180	0.196	0.015

Table A7: The timing of the different phases present in a rugby goal kick (Participant 2)

		K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
Max Knee Flexion	Angle	91.14	91.64	91.97	88.33	88.43	87.29	89.26	89.58	88.97	89.88	89.65	1.45
	Position	59%	65%	60%	61%	61%	62%	61%	63%	63%	63%	62%	2%
Max Hip Flexion	Angle	-13.49	-19.22	-12.93	-12.36	-14.16	-16.18	-17.26	-18.97	-17.62	-18.16	-16.03	2.46
	Position	49%	55%	51%	52%	51%	52%	52%	52%	52%	53%	52%	1%

Table A8: The key events during the goal kick (Participant 2)

	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
Distance of Launch (m)	1.401	1.431	1.311	1.326	1.328	1.389	1.355	1.383	1.373	1.373	1.367	0.035

Table A9: (Participant 2)

	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
S1/K1	0	0	0	0	0	0	0	0	0	0	0%	0%
K2	36%	39%	37%	38%	37%	37%	38%	37%	38%	38%	37%	1%
S2	49%	55%	49%	50%	50%	51%	51%	52%	52%	52%	51%	2%
K3	69%	75%	70%	72%	71%	72%	71%	73%	73%	73%	72%	2%
S3	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	0%

Table A10: The magnitude and position of maximum knee and hip flexion (Participant 2)

	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
S1/K1 to K2	0.245	0.250	0.245	0.245	0.245	0.240	0.250	0.235	0.240	0.240	0.244	0.005
K2 to S2	0.090	0.100	0.085	0.080	0.090	0.090	0.085	0.095	0.090	0.095	0.090	0.006
S2 to K3	0.135	0.125	0.140	0.140	0.140	0.140	0.135	0.140	0.135	0.135	0.137	0.005
K3 to S3	0.210	0.160	0.200	0.180	0.195	0.180	0.190	0.170	0.175	0.170	0.183	0.015
Whole Kick	0.68	0.635	0.67	0.645	0.67	0.65	0.66	0.64	0.64	0.64	0.653	0.016

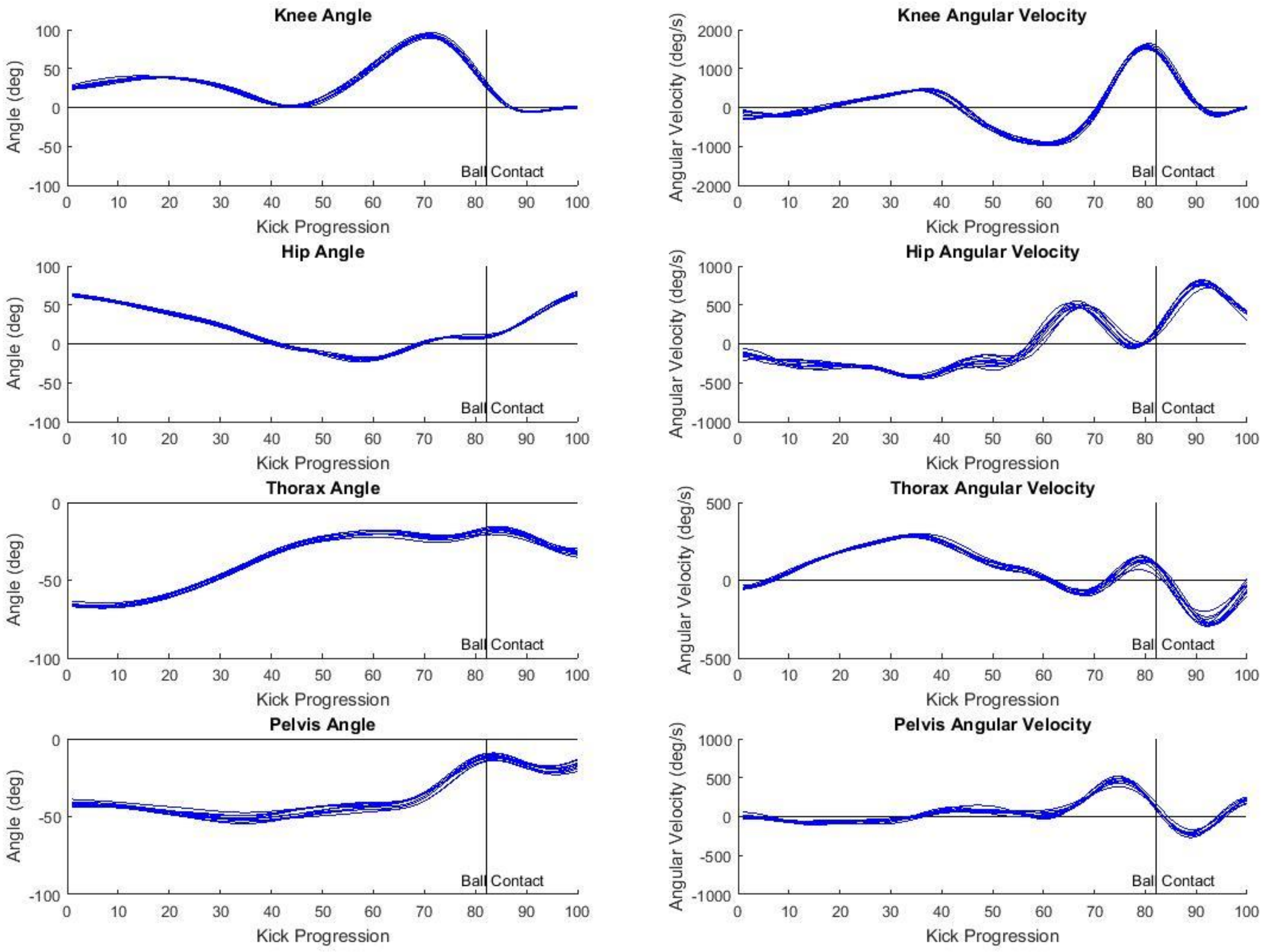

Figure A3: Joint kinematics of Participant 3

Participant 3

Table A11: Peak velocities, along with the position at which they occur (Participant 3)

		K1	**K2**	**K3**	**K4**	**K5**	**K6**	**K7**	**K8**	**K9**	**K10**	**Mean**	**STD**
Knee	Peak Velocity (°/s)	1540.72	1590.78	1496.05	1550.64	1597.77	1540.63	1596.94	1549.89	1613.91	1648.91	1572.62	42.40
	Peak Velocity Position	74%	78%	76%	73%	75%	74%	75%	75%	75%	77%	75%	1%
	Peak to BC (s)	0.155	0.130	0.140	0.155	0.145	0.150	0.145	0.150	0.145	0.130	0.145	0.009
Hip	Peak Velocity (°/s)	489.75	480.20	466.17	469.53	553.02	521.14	506.69	464.01	500.90	513.22	496.46	26.87
	Peak Velocity Position	63%	65%	63%	61%	63%	61%	62%	64%	64%	64%	63%	1%
	Peak to BC (s)	0.220	0.205	0.215	0.225	0.215	0.225	0.220	0.215	0.210	0.200	0.215	0.008

	Peak Velocity (°/s)	383.21	491.46	492.70	492.00	489.59	520.44	517.28	432.66	463.02	451.31	473.37	39.79
	Peak Velocity Position	69%	73%	71%	69%	71%	70%	70%	70%	70%	71%	70%	1%
Pelvis	Peak to BC (s)	0.185	0.160	0.165	0.180	0.170	0.175	0.175	0.180	0.175	0.160	0.173	0.008
	Peak Velocity (°/s)	116.92	158.42	68.06	149.00	124.93	150.46	148.16	113.86	131.97	133.25	129.50	24.95
	Peak Velocity Position	73%	77%	74%	73%	76%	74%	74%	75%	74%	77%	75%	1%
Thorax	Peak to BC (s)	0.165	0.135	0.150	0.155	0.140	0.150	0.155	0.150	0.150	0.130	0.148	0.010
	Peak Velocity (m/s)	24.06	23.73	24.27	23.94	24.14	23.84	24.10	23.98	24.18	24.45	24.07	0.20
	Peak Velocity Position	76%	79%	77%	76%	77%	77%	76%	77%	77%	79%	77%	1%
Foot	Peak to BC (s)	0.145	0.125	0.130	0.140	0.135	0.135	0.140	0.140	0.135	0.120	0.135	0.007

Table A12: The timing of the different phases present in a rugby goal kick (Participant 3)

		K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
Max Knee Flexion	Angle	91.45	93.57	89.10	91.88	92.80	90.91	95.08	91.49	93.24	96.16	92.57	1.96
	Position	66%	68%	67%	65%	67%	66%	66%	67%	67%	68%	67%	1%
Max Hip Flexion	Angle	-18.25	-19.60	-18.96	-18.83	-22.41	-23.04	-20.58	-17.53	-18.65	-20.75	-19.86	1.71
	Position	55%	56%	55%	53%	55%	53%	55%	56%	56%	56%	55%	1%

Table A13: The key events during the goal kick (Participant 3)

	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
Distance of Launch (m)	1.494	1.565	1.566	1.601	1.514	1.571	1.598	1.551	1.569	1.587	1.562	0.032

Table A14: The length of the final stride before ball contact (Participant 3)

	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
S1/K1	0	0	0	0	0	0	0	0	0	0	0%	0%
K2	39%	44%	40%	43%	42%	41%	41%	43%	41%	42%	42%	2%
S2	54%	61%	59%	57%	58%	58%	58%	58%	58%	60%	58%	2%
K3	76%	79%	77%	76%	78%	77%	77%	77%	77%	79%	77%	1%
S3	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	0%

Table A15: The magnitude and position of maximum knee and hip flexion (Participant 3)

	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD

S1/K1 to K2	0.235	0.260	0.230	0.250	0.245	0.235	0.240	0.260	0.240	0.235	0.243	0.011
K2 to S2	0.090	0.095	0.110	0.080	0.090	0.100	0.100	0.085	0.100	0.100	0.095	0.009
S2 to K3	0.130	0.110	0.105	0.110	0.115	0.110	0.110	0.115	0.110	0.105	0.112	0.007
K3 to S3	0.145	0.120	0.130	0.140	0.130	0.135	0.135	0.140	0.135	0.120	0.133	0.008
Whole Kick	0.6	0.585	0.575	0.58	0.58	0.58	0.585	0.6	0.585	0.56	0.583	0.012

Participant 4

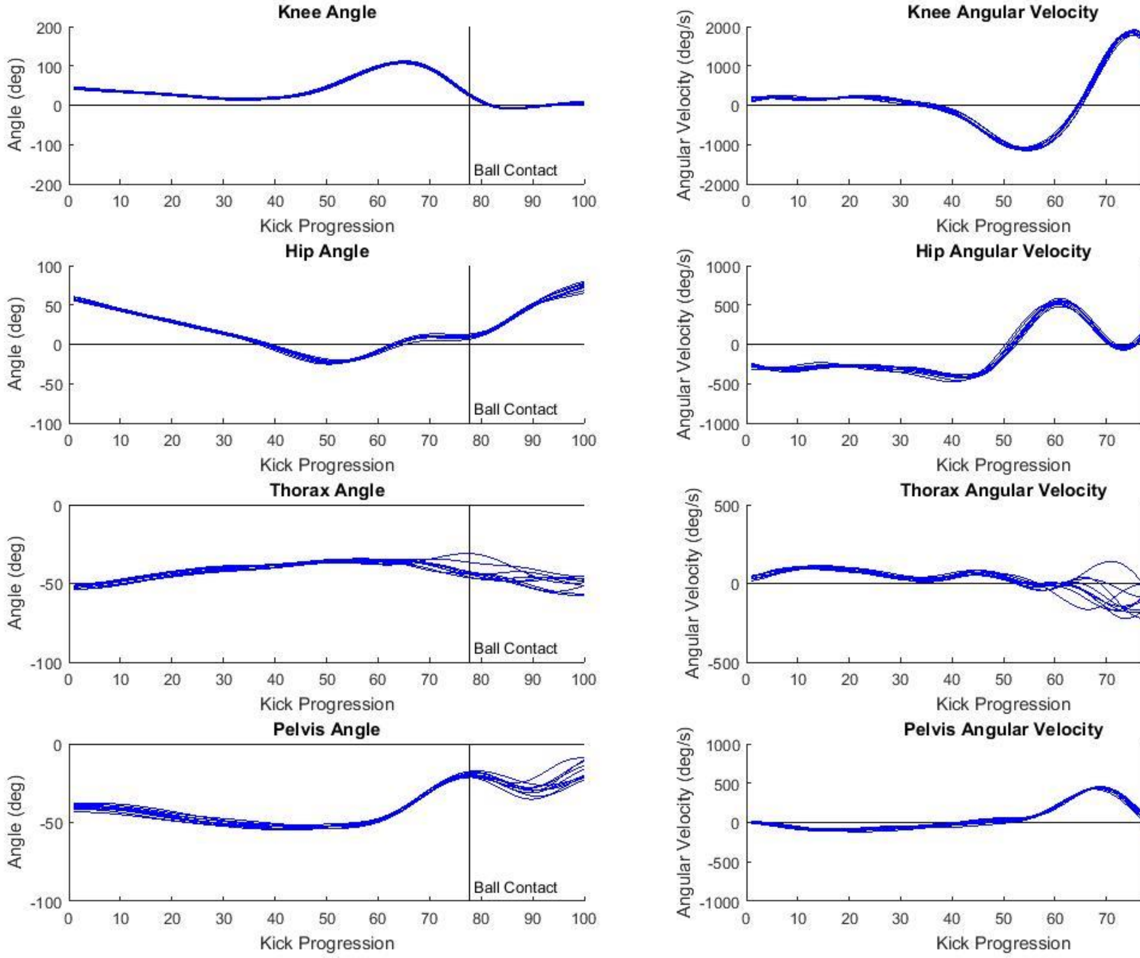

Figure A4: Joint kinematics of Participant 4

Table A16: Peak velocities, along with the position at which they occur (Participant 4)

		K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
Knee	Peak Velocity (°/s)	1883.38	1913.71	1827.32	1784.40	1862.10	1832.74	1879.87	1861.06	1781.81	1858.71	1848.51	40.19
	Peak Velocity Position	71%	72%	69%	70%	71%	68%	66%	69%	70%	68%	69%	2%
	Peak to BC (s)	0.175	0.160	0.185	0.165	0.175	0.195	0.200	0.195	0.175	0.195	0.182	0.013
Hip	Peak Velocity (°/s)	559.73	548.25	503.73	532.85	534.26	549.25	585.31	531.79	480.92	548.23	537.43	27.49
	Peak Velocity Position	58%	58%	56%	58%	59%	55%	55%	56%	58%	55%	57%	1%
	Peak to BC (s)	0.250	0.235	0.260	0.235	0.245	0.270	0.270	0.270	0.245	0.270	0.255	0.014
Pelvis	Peak Velocity (°/s)	449.18	457.81	444.43	440.30	421.73	444.11	450.80	436.80	434.01	447.35	442.65	9.58
	Peak Velocity Position	64%	65%	63%	64%	65%	62%	61%	63%	64%	63%	63%	1%

	Peak to BC (s)	0.215	0.195	0.220	0.200	0.210	0.230	0.230	0.230	0.210	0.225	0.217	0.012
	Peak Velocity (°/s)	-3.43	30.93	4.69	4.77	-3.17	28.36	39.69	140.29	9.18	11.66	26.30	40.48
	Peak Velocity Position	53%	52%	52%	55%	53%	60%	59%	65%	60%	50%	56%	5%
Thorax	Peak to BC (s)	0.285	0.270	0.285	0.250	0.280	0.245	0.245	0.215	0.235	0.305	0.262	0.026
	Peak Velocity (m/s)	22.84	22.63	22.44	22.88	27.75	22.24	22.61	23.20	23.10	22.66	23.24	1.53
	Peak Velocity Position	72%	73%	71%	71%	73%	69%	68%	70%	72%	69%	71%	2%
Foot	Peak to BC (s)	0.170	0.155	0.175	0.160	0.160	0.190	0.190	0.185	0.165	0.185	0.174	0.013

Table A17: The timing of the different phases present in a rugby goal kick (Participant 4)

		K1	**K2**	**K3**	**K4**	**K5**	**K6**	**K7**	**K8**	**K9**	**K10**	**Mean**	**STD**
Max Knee Flexion	Angle	111.30	112.54	108.24	107.10	109.76	109.99	111.33	109.93	105.81	111.04	109.71	1.98
	Position	62%	62%	60%	60%	61%	59%	58%	60%	62%	60%	60%	1%
Max Hip Flexion	Angle	-21.12	-23.74	-21.66	-19.98	-21.73	-22.22	-23.06	-25.32	-23.18	-24.33	-22.63	1.52
	Position	50%	50%	49%	49%	51%	48%	47%	48%	50%	47%	49%	1%

Table A18: The key events during the goal kick (Participant 4)

	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
Distance of Launch (m)	1.382	1.397	1.406	1.401	1.417	1.401	1.379	0.658	1.445	1.414	1.330	0.225

Table A 19: The length of the final stride before ball contact (Participant 4)

	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
S1/K1	0	0	0	0	0	0	0	0	0	0	0%	0%
K2	31%	32%	30%	31%	33%	30%	29%	31%	32%	31%	31%	1%
S2	53%	52%	52%	51%	53%	50%	48%	50%	53%	50%	51%	2%
K3	73%	73%	71%	72%	73%	69%	69%	71%	73%	70%	71%	2%
S3	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	0%

Table A20: The magnitude and position of maximum knee and hip flexion (Participant 4)

	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
S1/K1 to K2	0.185	0.180	0.180	0.170	0.195	0.180	0.170	0.195	0.185	0.185	0.183	0.009
K2 to S2	0.130	0.115	0.130	0.115	0.120	0.120	0.115	0.115	0.125	0.115	0.120	0.006
S2 to K3	0.120	0.120	0.115	0.115	0.120	0.120	0.125	0.130	0.115	0.125	0.121	0.005
K3 to S3	0.165	0.150	0.170	0.155	0.160	0.185	0.185	0.180	0.160	0.180	0.169	0.013
Whole Kick	0.6	0.565	0.595	0.555	0.595	0.605	0.595	0.62	0.585	0.605	0.592	0.019

Participant 5

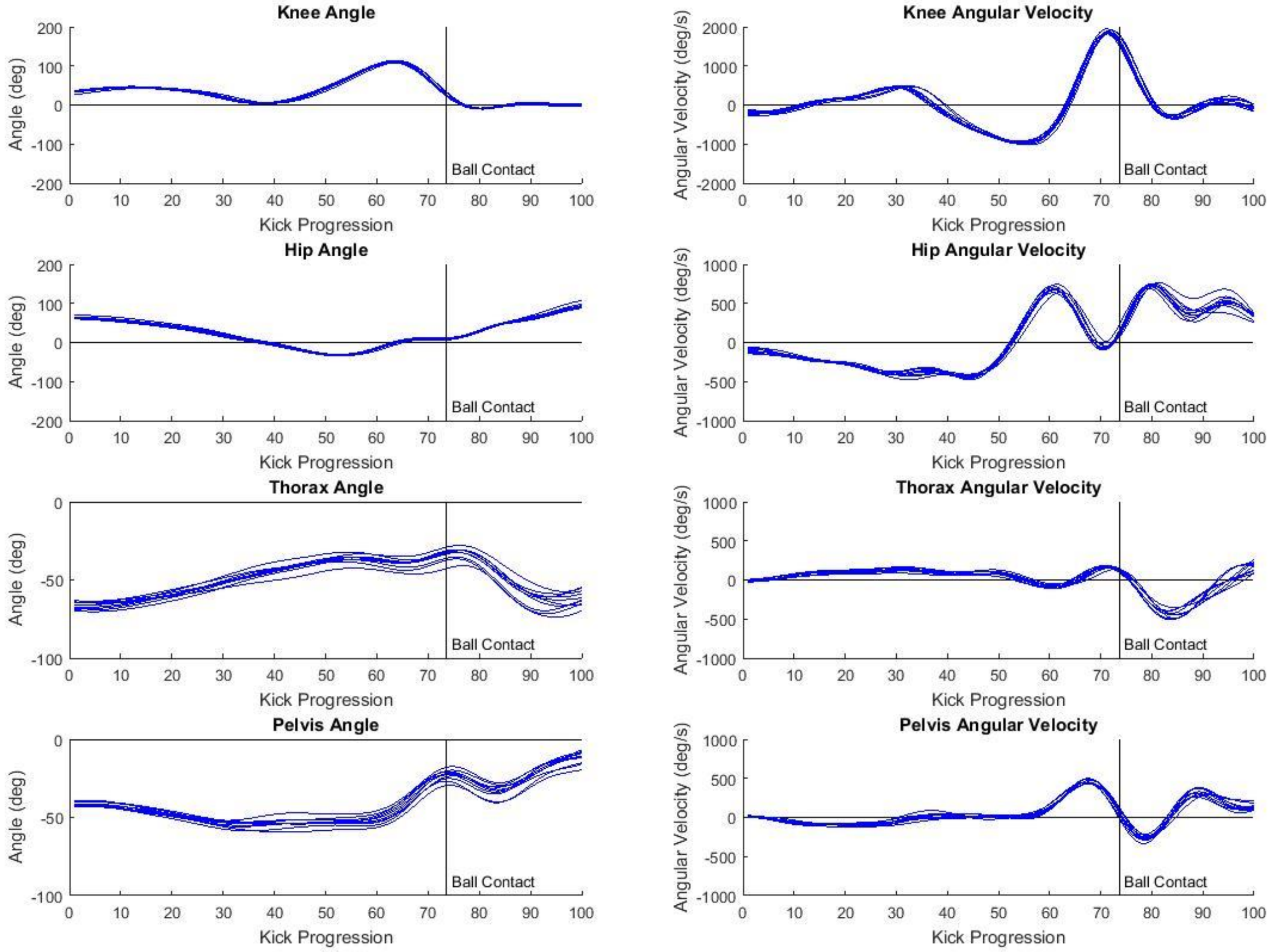

Figure A5: Joint kinematics of Participant 5

Table A21: Peak velocities, along with the position at which they occur (Participant 5)

		K1	**K2**	**K3**	**K4**	**K5**	**K6**	**K7**	**K8**	**K9**	**K10**	**Mean**	**STD**
Knee	Peak Velocity (°/s)	1884.96	1950.07	1840.63	1825.71	1865.61	1915.59	1847.04	1915.69	1821.93	1879.21	1874.64	40.44
	Peak Velocity Position	68%	69%	69%	68%	67%	68%	66%	68%	65%	68%	68%	1%
	Peak to BC (s)	0.225	0.225	0.215	0.225	0.225	0.215	0.245	0.220	0.245	0.225	0.227	0.010
Hip	Peak Velocity (°/s)	665.17	685.37	698.17	666.34	729.23	643.59	694.42	747.37	638.71	678.80	684.72	32.78
	Peak Velocity Position	58%	59%	58%	58%	57%	59%	56%	58%	56%	58%	58%	1%
	Peak to BC (s)	0.290	0.295	0.285	0.295	0.295	0.280	0.315	0.290	0.310	0.295	0.295	0.010

	Peak Velocity (°/s)	443.01	446.31	447.39	452.72	500.57	435.68	474.15	429.51	450.84	496.38	457.66	23.26
	Peak Velocity Position	64%	65%	65%	64%	64%	65%	62%	64%	62%	65%	64%	1%
Pelvis	Peak to BC (s)	0.250	0.255	0.240	0.250	0.250	0.240	0.270	0.250	0.270	0.250	0.253	0.010
	Peak Velocity (°/s)	137.45	188.06	179.63	152.45	166.71	156.31	155.44	167.29	179.45	176.60	165.94	14.74
	Peak Velocity Position	69%	68%	69%	68%	67%	68%	66%	67%	65%	68%	67%	1%
Thorax	Peak to BC (s)	0.215	0.230	0.215	0.225	0.225	0.220	0.245	0.230	0.245	0.225	0.228	0.010
	Peak Velocity (m/s)	23.24	24.16	23.37	23.36	23.91	23.86	23.56	23.38	23.23	23.71	23.58	0.30
	Peak Velocity Position	69%	70%	70%	68%	69%	68%	66%	69%	67%	70%	69%	1%
Foot	Peak to BC (s)	0.215	0.215	0.205	0.220	0.215	0.215	0.240	0.215	0.235	0.215	0.219	0.010

Table A22: The timing of the different phases present in a rugby goal kick (Participant 5)

		K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
Max Knee Flexion	Angle	109.87	113.01	109.59	107.52	111.19	109.03	112.16	113.74	108.45	110.93	110.55	1.91
	Position	60%	61%	61%	60%	59%	61%	58%	60%	58%	61%	60%	1%
Max Hip Flexion	Angle	-30.42	-33.84	-33.04	-32.15	-34.37	-33.64	-33.61	-34.67	-34.31	-33.52	-33.36	1.19
	Position	50%	51%	50%	50%	49%	51%	48%	50%	49%	51%	50%	1%

Table A23: The key events during the goal kick (Participant 5)

	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
Distance of Launch (m)	1.519	1.612	1.583	1.575	1.623	1.572	1.669	1.628	1.629	1.635	1.605	0.040

Table A24: The length of the final stride before ball contact (Participant 5)

	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
S1/K1	0	0	0	0	0	0	0	0	0	0	0%	0%
K2	36%	35%	34%	36%	33%	36%	33%	35%	33%	35%	35%	1%
S2	53%	53%	53%	52%	52%	53%	50%	53%	51%	54%	52%	1%
K3	70%	71%	71%	70%	70%	70%	67%	70%	68%	70%	70%	1%
S3	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	0%

Table A25: The magnitude and position of maximum knee and hip flexion (Participant 5)

	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
S1/K1 to K2	0.250	0.250	0.235	0.250	0.230	0.245	0.235	0.240	0.235	0.250	0.242	0.008
K2 to S2	0.115	0.135	0.130	0.110	0.130	0.115	0.125	0.125	0.130	0.130	0.125	0.008
S2 to K3	0.120	0.125	0.120	0.125	0.120	0.115	0.120	0.120	0.120	0.115	0.120	0.003
K3 to S3	0.210	0.210	0.200	0.210	0.210	0.205	0.235	0.210	0.225	0.210	0.213	0.010
Whole Kick	0.695	0.72	0.685	0.695	0.69	0.68	0.715	0.695	0.71	0.705	0.699	0.013

Participant 6

Table A26: Peak velocities, along with the position at which they occur (Participant 6)

		K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
Knee	Peak Velocity (°/s)	1578.95	1616.76	1586.64	1538.64	1487.92	1584.88	1636.49	1586.64	1608.25	1601.44	1582.66	40.04
	Peak Velocity Position	71%	73%	70%	70%	74%	69%	76%	74%	73%	75%	73%	2%
	Peak to BC (s)	0.203	0.185	0.203	0.210	0.173	0.220	0.158	0.170	0.175	0.165	0.186	0.020
Hip	Peak Velocity (°/s)	438.25	487.42	479.01	418.02	402.49	496.78	450.44	474.97	459.49	447.68	455.46	28.76
	Peak Velocity Position	73%	64%	61%	61%	64%	72%	67%	63%	64%	64%	65%	4%
	Peak to BC (s)	0.185	0.250	0.263	0.275	0.240	0.198	0.215	0.240	0.240	0.235	0.234	0.026
Pelvis	Peak Velocity (°/s)	360.03	334.69	323.33	406.91	475.68	382.50	353.42	386.03	388.88	412.66	382.41	41.69
	Peak Velocity Position	65%	68%	65%	65%	70%	64%	70%	69%	68%	69%	68%	2%
	Peak to BC (s)	0.243	0.220	0.235	0.243	0.198	0.255	0.193	0.200	0.210	0.200	0.220	0.022
Thorax	Peak Velocity (°/s)	64.05	51.95	76.59	52.28	85.14	51.41	106.75	50.14	78.51	131.99	74.88	25.91
	Peak Velocity Position	68%	72%	68%	66%	72%	66%	73%	69%	70%	72%	69%	2%
	Peak to BC (s)	0.225	0.195	0.218	0.238	0.188	0.245	0.178	0.200	0.200	0.185	0.207	0.022
Foot	Peak Velocity (m/s)	23.36	23.04	22.99	23.48	23.01	23.56	23.26	23.19	23.40	23.54	23.28	0.21
	Peak Velocity Position	73%	76%	72%	72%	76%	71%	78%	75%	75%	76%	74%	2%
	Peak to BC (s)	0.190	0.170	0.188	0.198	0.160	0.205	0.143	0.160	0.165	0.155	0.173	0.019

Table A27: The timing of the different phases present in a rugby goal kick (Participant 6)

		K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
Max Knee Flexion	Angle	101.43	103.58	103.71	99.15	97.10	101.95	103.01	104.03	103.68	101.73	101.94	2.14
	Position	63%	65%	63%	62%	66%	62%	68%	65%	65%	66%	64%	2%
Max Hip Flexion	Angle	-26.70	-30.52	-26.77	-27.78	-28.76	-28.55	-28.91	-29.75	-29.02	-29.14	-28.59	1.15
	Position	53%	57%	53%	53%	56%	52%	58%	55%	55%	55%	55%	2%

Table A28: The key events during the goal kick (Participant 6)

	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD

Distance of Launch (m)	1.844	1.832	1.825	1.877	1.886	1.884	1.826	1.836	1.894	1.879	1.858	0.027

Table A29: The length of the final stride before ball contact (Participant 6)

	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
S1/K1	0	0	0	0	0	0	0	0	0	0	0%	0%
K2	37%	38%	36%	36%	38%	36%	40%	36%	39%	39%	37%	2%
S2	58%	62%	58%	58%	62%	58%	62%	62%	61%	62%	60%	2%
K3	73%	76%	73%	73%	77%	72%	79%	76%	76%	76%	75%	2%
S3	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	0%

Table A30: The magnitude and position of maximum knee and hip flexion (Participant 6)

	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
S1/K1 to K2	0.255	0.265	0.248	0.253	0.255	0.255	0.260	0.235	0.255	0.255	0.254	0.008
K2 to S2	0.150	0.165	0.150	0.150	0.160	0.163	0.143	0.165	0.150	0.150	0.155	0.008
S2 to K3	0.108	0.100	0.100	0.105	0.098	0.103	0.113	0.095	0.095	0.090	0.101	0.007
K3 to S3	0.185	0.165	0.183	0.193	0.153	0.198	0.138	0.155	0.160	0.155	0.168	0.020
Whole Kick	0.6975	0.695	0.68	0.7	0.665	0.7175	0.6525	0.65	0.66	0.65	0.677	0.025

Participant 7

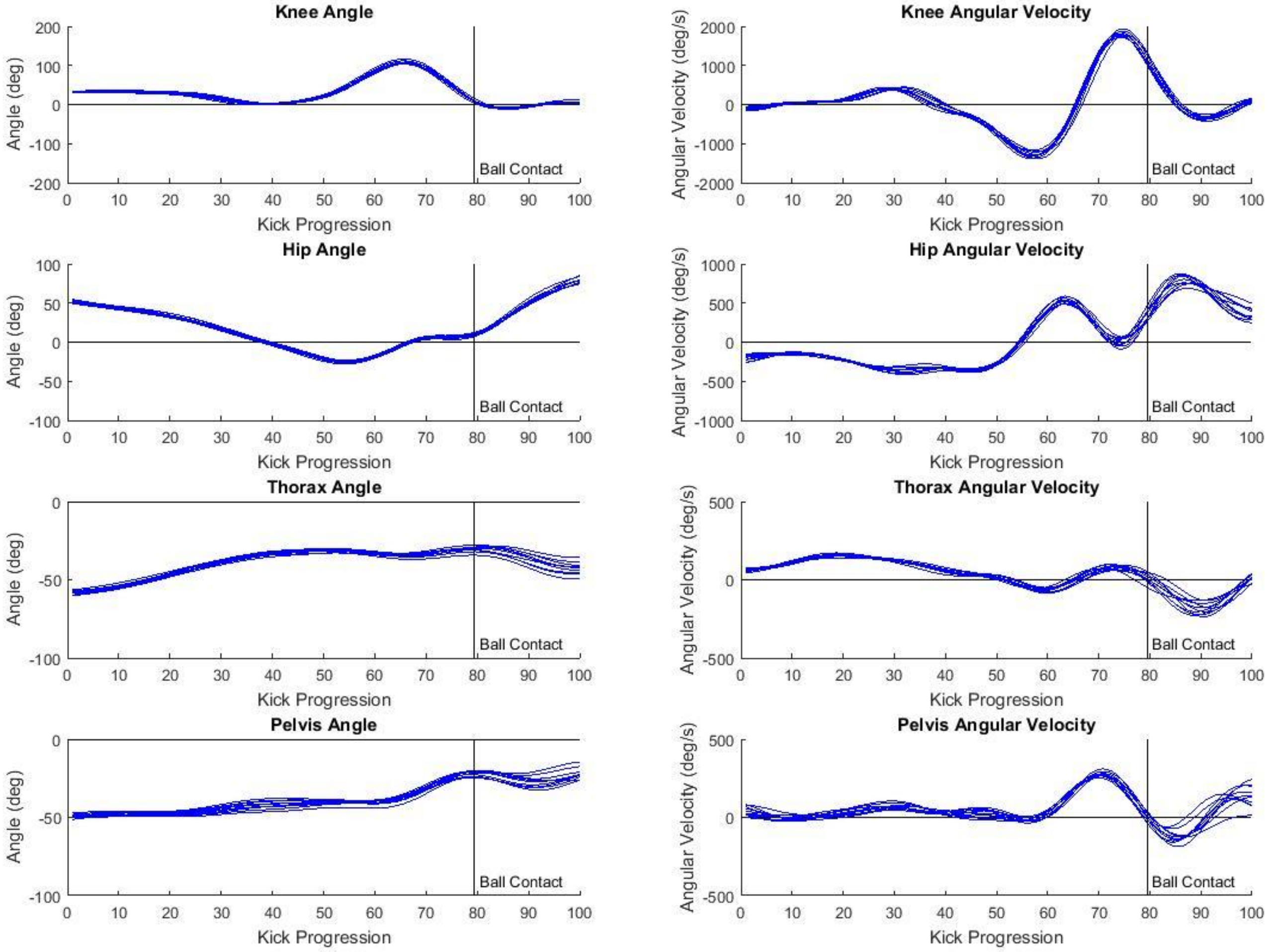

Figure A7: Joint kinematics of Participant 7

Table A31: Peak velocities, along with the position at which they occur (Participant 7)

		K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
Knee	Peak Velocity (°/s)	1767.41	1878.28	1725.41	1781.37	1757.99	1859.09	1807.72	1805.73	1935.56	1807.31	1812.59	59.41
	Peak Velocity Position	68%	70%	69%	68%	69%	68%	70%	68%	71%	68%	69%	1%
	Peak to BC (s)	0.205	0.195	0.190	0.195	0.200	0.200	0.185	0.205	0.195	0.200	0.197	0.006
Hip	Peak Velocity (°/s)	485.37	574.77	491.82	521.67	492.19	566.06	520.78	517.65	587.84	539.19	529.73	34.53
	Peak Velocity Position	58%	60%	59%	59%	59%	59%	60%	59%	61%	58%	59%	1%
	Peak to BC (s)	0.265	0.255	0.250	0.255	0.260	0.260	0.245	0.265	0.260	0.260	0.258	0.006

	Peak Velocity (°/s)	265.02	280.16	253.85	268.11	269.68	292.53	277.50	267.68	309.83	277.56	276.19	14.91
	Peak Velocity Position	65%	66%	65%	65%	66%	65%	66%	64%	67%	65%	65%	1%
Pelvis	Peak to BC (s)	0.225	0.220	0.215	0.215	0.220	0.220	0.210	0.230	0.220	0.220	0.220	0.005
	Peak Velocity (°/s)	60.46	98.98	85.12	91.29	96.78	90.79	72.62	71.97	60.26	74.00	80.23	13.56
	Peak Velocity Position	66%	67%	68%	67%	67%	69%	68%	65%	69%	67%	67%	1%
Thorax	Peak to BC (s)	0.215	0.210	0.195	0.205	0.210	0.195	0.200	0.225	0.205	0.205	0.207	0.009
	Peak Velocity (m/s)	21.55	21.81	21.85	21.84	21.65	21.82	21.77	21.65	22.21	22.07	21.82	0.19
	Peak Velocity Position	72%	72%	73%	72%	73%	71%	73%	70%	74%	72%	72%	1%
Foot	Peak to BC (s)	0.180	0.180	0.165	0.175	0.175	0.180	0.165	0.190	0.175	0.175	0.176	0.007

Table A32: The timing of the different phases present in a rugby goal kick (Participant 7)

		K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
Max Knee Flexion	Angle	106.40	108.89	103.07	105.99	103.91	111.76	105.77	104.51	116.35	107.60	107.43	3.82
	Position	61%	62%	61%	61%	62%	60%	62%	60%	63%	60%	61%	1%
Max Hip Flexion	Angle	-23.12	-25.58	-24.69	-24.27	-23.24	-26.18	-26.15	-25.94	-27.78	-26.90	-25.39	1.45
	Position	50%	52%	51%	50%	52%	51%	52%	51%	53%	50%	51%	1%

Table A33: The key events during the goal kick (Participant 7)

	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
Distance of Launch (m)	1.433	1.487	1.488	1.490	1.428	1.441	1.532	1.496	1.547	1.518	1.486	0.039

Table A34: The length of the final stride before ball contact (Participant 7)

	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
S1/K1	0	0	0	0	0	0	0	0	0	0	0%	0%
K2	34%	37%	35%	34%	36%	35%	39%	34%	39%	35%	36%	2%
S2	52%	55%	54%	53%	54%	51%	55%	52%	56%	54%	54%	2%
K3	72%	73%	74%	72%	73%	73%	75%	73%	74%	73%	73%	1%
S3	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	0%

Table A35: The magnitude and position of maximum knee and hip flexion (Participant 7)

	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD

1/K1 to K2	0.215	0.235	0.215	0.210	0.230	0.220	0.240	0.220	0.260	0.220	0.227	0.015
K2 to S2	0.115	0.115	0.115	0.115	0.115	0.100	0.100	0.115	0.115	0.115	0.112	0.006
S2 to K3	0.130	0.120	0.120	0.120	0.125	0.140	0.125	0.130	0.120	0.120	0.125	0.007
K3 to S3	0.175	0.170	0.160	0.170	0.170	0.170	0.155	0.175	0.170	0.170	0.169	0.006
Whole Kick	0.635	0.64	0.61	0.615	0.64	0.63	0.62	0.64	0.665	0.625	0.632	0.016

Participant 8

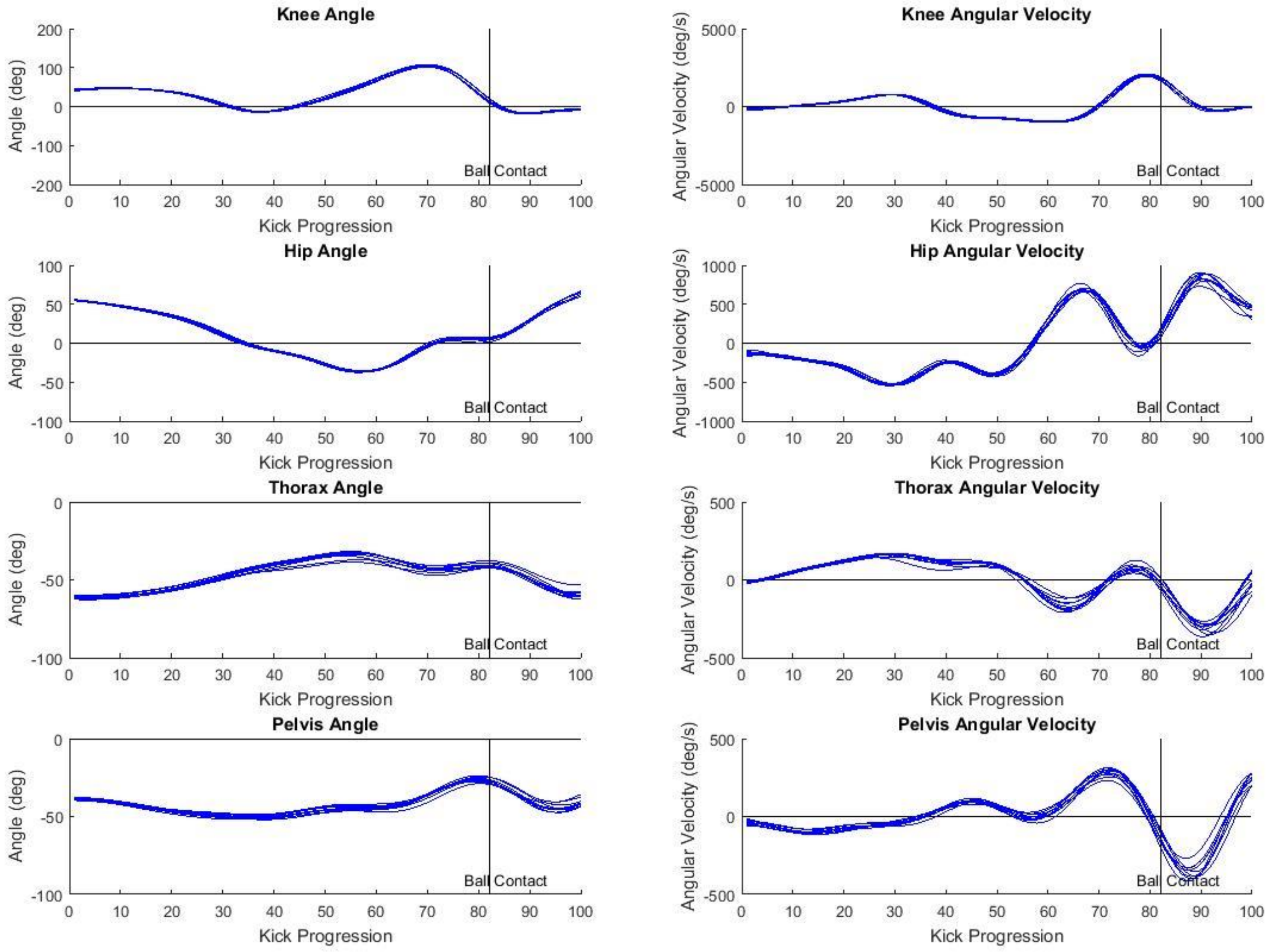

Figure A8: Joint kinematics of Participant 8

Table A36: Peak velocities, along with the position at which they occur (Participant 8)

		K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
Knee	Peak Velocity (°/s)	1984.88	2064.74	1936.82	1990.02	1955.15	1987.74	2068.90	2008.14	2049.40	2091.44	2013.73	49.40
	Peak Velocity Position	76%	75%	75%	78%	73%	76%	78%	74%	75%	76%	76%	2%
	Peak to BC (s)	0.135	0.145	0.145	0.130	0.155	0.135	0.125	0.155	0.145	0.135	0.141	0.010
Hip	Peak Velocity (°/s)	690.46	678.10	710.11	674.43	684.95	667.38	710.38	680.21	768.39	666.13	693.05	29.08
	Peak Velocity Position	65%	64%	63%	66%	62%	65%	67%	63%	64%	65%	64%	1%
	Peak to BC (s)	0.200	0.210	0.210	0.195	0.220	0.200	0.190	0.220	0.210	0.200	0.206	0.010

	Peak Velocity (°/s)	314.61	309.74	231.48	277.46	269.02	283.29	253.73	301.20	303.40	291.80	283.57	25.05
	Peak Velocity Position	70%	69%	68%	71%	66%	68%	72%	67%	69%	69%	69%	2%
Pelvis	Peak to BC (s)	0.170	0.180	0.185	0.170	0.200	0.180	0.165	0.195	0.180	0.175	0.180	0.010
	Peak Velocity (°/s)	95.76	84.11	42.88	69.08	86.01	53.15	85.97	64.69	125.88	72.75	78.03	22.15
	Peak Velocity Position	74%	74%	72%	75%	71%	74%	76%	72%	74%	73%	74%	1%
Thorax	Peak to BC (s)	0.145	0.150	0.160	0.145	0.170	0.150	0.140	0.165	0.150	0.150	0.153	0.009
	Peak Velocity (m/s)	24.47	24.57	23.81	24.29	24.25	24.40	25.39	24.59	24.95	24.31	24.50	0.40
	Peak Velocity Position	79%	78%	76%	80%	75%	78%	81%	76%	78%	78%	78%	2%
Foot	Peak to BC (s)	0.120	0.130	0.135	0.115	0.145	0.125	0.110	0.140	0.130	0.125	0.128	0.010

Table A37: The timing of the different phases present in a rugby goal kick (Participant 8)

		K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
Max Knee Flexion	Angle	105.74	107.03	101.80	105.13	101.09	103.18	107.65	105.89	106.53	107.68	105.17	2.25
	Position	67%	66%	66%	69%	65%	68%	70%	66%	67%	67%	67%	1%
Max Hip Flexion	Angle	-36.35	-37.55	-36.12	-36.64	-36.72	-36.09	-36.63	-37.46	-37.01	-35.20	-36.58	0.66
	Position	56%	54%	54%	57%	53%	55%	58%	54%	56%	55%	55%	1%

Table A38: The key events during the goal kick (Participant 8)

	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
Distance of Launch (m)	1.502	1.508	1.438	1.477	1.492	1.501	1.547	1.520	1.550	1.502	1.504	0.031

Table A39: The length of the final stride before ball contact (Participant 8)

	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
S1/K1	0	0	0	0	0	0	0	0	0	0	0%	0%
K2	37%	36%	36%	36%	35%	37%	41%	36%	37%	35%	37%	2%
S2	58%	57%	56%	61%	55%	59%	60%	56%	59%	58%	58%	2%
K3	80%	78%	77%	80%	76%	79%	81%	76%	79%	79%	79%	2%
S3	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	0%

Table A 40: The magnitude and position of maximum knee and hip flexion (Participant 8)

	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD

S1/K1 to K2	0.210	0.210	0.205	0.210	0.205	0.210	0.240	0.215	0.215	0.200	0.212	0.011
K2 to S2	0.120	0.120	0.115	0.145	0.115	0.125	0.110	0.120	0.130	0.130	0.123	0.010
S2 to K3	0.120	0.125	0.120	0.110	0.120	0.115	0.120	0.120	0.115	0.115	0.118	0.004
K3 to S3	0.115	0.125	0.130	0.115	0.140	0.120	0.110	0.140	0.125	0.120	0.124	0.010
Whole Kick	0.565	0.58	0.57	0.58	0.58	0.57	0.58	0.595	0.585	0.565	0.577	0.009

Participant 9

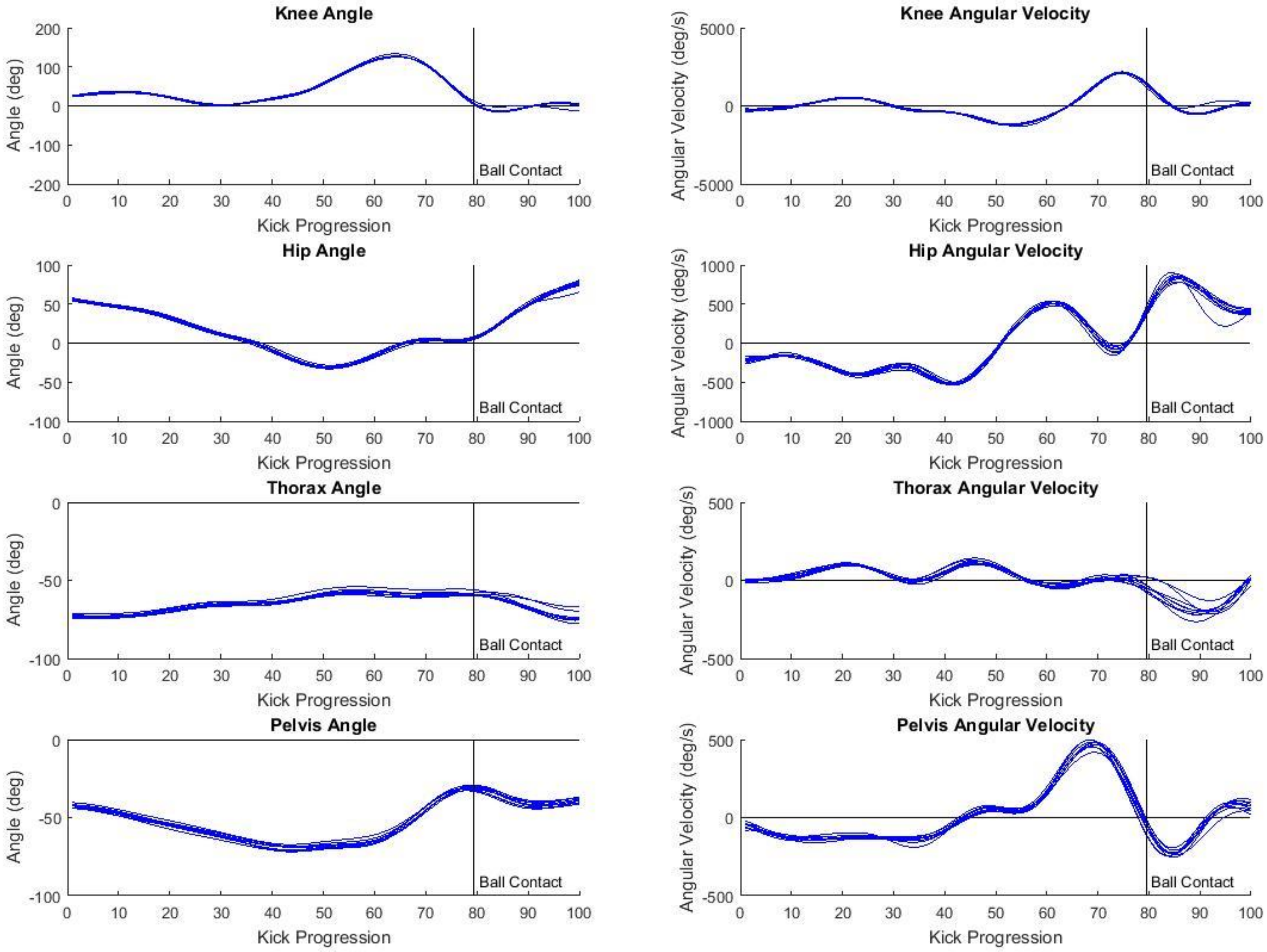

Figure A9: Joint kinematics of Participant 9

Table A41: Peak velocities, along with the position at which they occur (Participant 9)

		K1	K2	K3	K4	K5	K6	K7	K8	K9	Mean	STD
Knee	Peak Velocity (°/s)	2087.65	2124.37	2130.47	2127.45	2135.77	2177.20	2158.47	2118.98	2083.64	2127.11	28.09
	Peak Velocity Position	70%	70%	71%	70%	71%	71%	71%	70%	69%	70%	1%
	Peak to BC (s)	0.190	0.190	0.180	0.180	0.185	0.185	0.175	0.190	0.195	0.186	0.006
Hip	Peak Velocity (°/s)	510.06	532.01	477.90	511.36	499.39	536.74	537.90	531.25	512.45	516.56	18.83
	Peak Velocity Position	59%	58%	59%	58%	58%	59%	58%	57%	56%	58%	1%
	Peak to BC (s)	0.265	0.265	0.255	0.255	0.265	0.265	0.250	0.270	0.270	0.262	0.007

	Peak Velocity (°/s)	495.65	417.93	484.49	453.71	498.17	477.93	457.63	466.99	484.27	470.75	23.71
	Peak Velocity Position	64%	65%	65%	64%	65%	66%	65%	65%	65%	65%	1%
Pelvis	Peak to BC (s)	0.230	0.220	0.215	0.215	0.220	0.215	0.210	0.220	0.220	0.218	0.005
	Peak Velocity (°/s)	17.61	39.46	20.87	11.88	35.42	37.40	15.67	19.13	34.91	25.82	10.16
	Peak Velocity Position	53%	51%	74%	52%	68%	52%	52%	69%	69%	60%	9%
Thorax	Peak to BC (s)	0.300	0.310	0.160	0.290	0.205	0.305	0.285	0.195	0.190	0.249	0.056
	Peak Velocity (m/s)	34.52	22.94	23.28	23.37	23.83	23.36	23.95	23.48	24.44	24.80	3.46
	Peak Velocity Position	45%	73%	74%	74%	74%	74%	74%	73%	73%	70%	9%
Foot	Peak to BC (s)	0.355	0.170	0.160	0.160	0.165	0.165	0.155	0.170	0.170	0.186	0.060

Table A42: The timing of the different phases present in a rugby goal kick (Participant 9)

		K1	K2	K3	K4	K5	K6	K7	K8	K9	Mean	STD
Max Knee Flexion	Angle	125.31	126.37	125.65	126.17	127.01	127.36	125.73	124.80	133.31	126.86	2.40
	Position	61%	61%	61%	60%	61%	62%	61%	61%	60%	61%	1%
Max Hip Flexion	Angle	-30.57	-31.99	-32.67	-30.11	-31.26	-31.47	-32.99	-32.43	-28.49	-31.33	1.35
	Position	49%	49%	49%	48%	50%	50%	48%	49%	48%	49%	1%

Table A43: The key events during the goal kick (Participant 9)

	K1	K2	K3	K4	K5	K6	K7	K8	K9	Mean	STD
Distance of Launch (m)	1.501	1.449	1.553	1.497	1.552	1.482	1.540	1.512	1.524	1.512	0.032

Table A44: The length of the final stride before ball contact (Participant 9)

	K1	K2	K3	K4	K5	K6	K7	K8	K9	Mean	STD
S1/K1	0	0	0	0	0	0	0	0	0	0%	0%
K2	31%	30%	28%	28%	29%	29%	28%	28%	29%	29%	1%
S2	53%	51%	53%	52%	54%	52%	52%	53%	52%	52%	1%
K3	74%	74%	75%	74%	75%	75%	75%	74%	73%	74%	1%
S3	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	0%

Table A 45: The magnitude and position of maximum knee and hip flexion (Participant 9)

	K1	K2	K3	K4	K5	K6	K7	K8	K9	Mean	STD
S1/K1 to K2	0.200	0.190	0.170	0.170	0.185	0.185	0.165	0.175	0.180	0.180	0.011
K2 to S2	0.140	0.135	0.155	0.145	0.160	0.150	0.145	0.160	0.140	0.148	0.009

S2 to K3	0.135	0.145	0.135	0.135	0.130	0.145	0.135	0.135	0.135	0.137	0.005
K3 to S3	0.165	0.165	0.155	0.155	0.160	0.160	0.150	0.165	0.165	0.160	0.006
Whole Kick	0.64	0.635	0.615	0.605	0.635	0.64	0.595	0.635	0.62	0.624	0.016

Participant 10

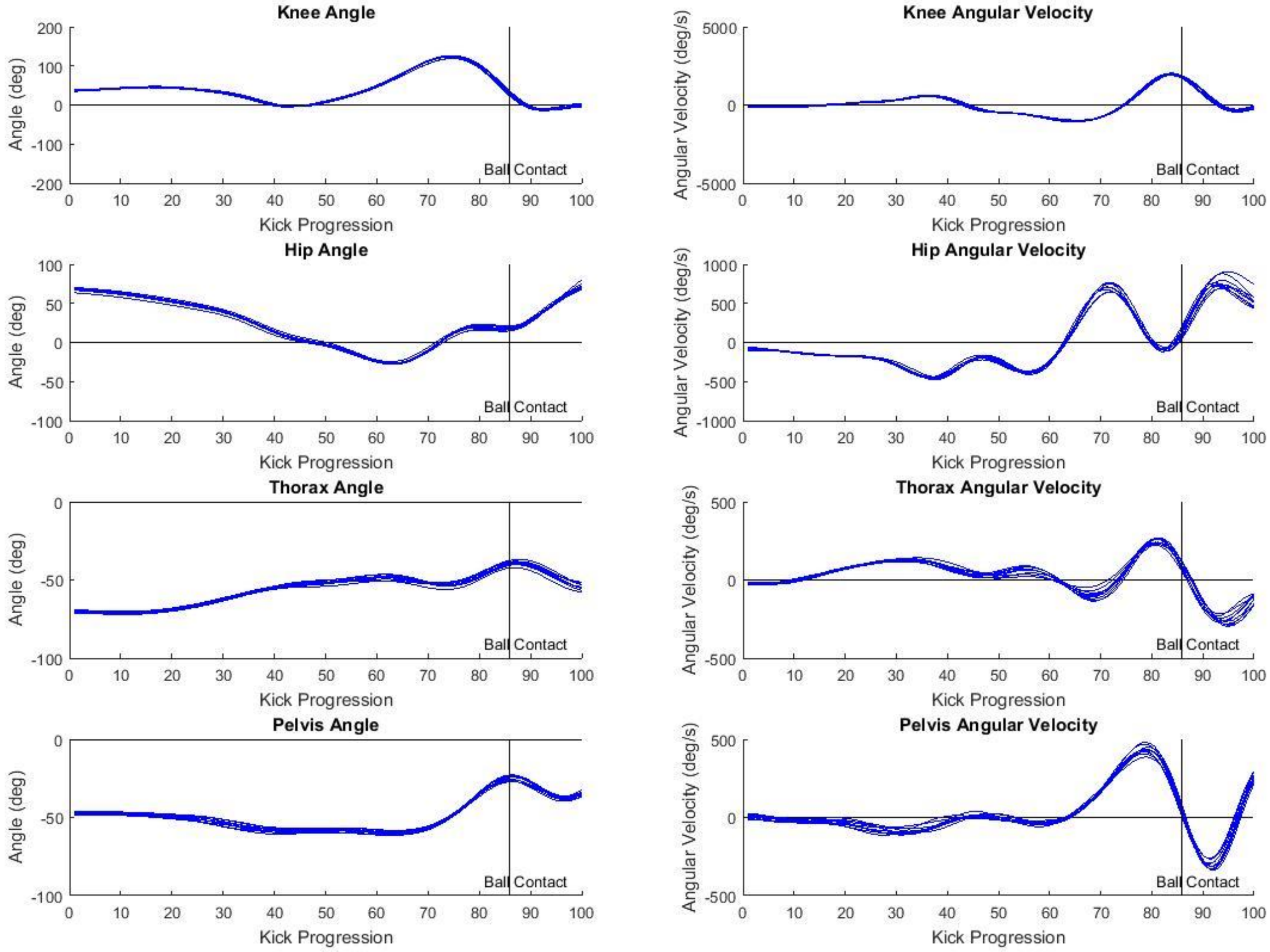

Figure A10: Joint kinematics of Participant 10

Table A46: Peak velocities, along with the position at which they occur (Participant 10)

		K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
Knee	Peak Velocity (°/s)	1916.16	2036.08	1953.58	2008.52	1962.67	1898.68	1953.30	2003.73	1981.13	2006.05	1971.99	41.18
	Peak Velocity Position	77%	78%	78%	80%	77%	75%	77%	79%	77%	80%	78%	1%
	Peak to BC (s)	0.165	0.150	0.165	0.140	0.160	0.180	0.165	0.145	0.160	0.145	0.158	0.012
Hip	Peak Velocity (°/s)	647.12	755.07	708.68	677.11	706.95	651.07	771.17	710.50	751.90	708.19	708.78	40.05
	Peak Velocity Position	66%	67%	67%	67%	66%	64%	65%	67%	66%	69%	66%	1%
	Peak to BC (s)	0.240	0.230	0.250	0.225	0.240	0.255	0.245	0.225	0.240	0.225	0.238	0.010

	Peak Velocity (°/s)	407.93	480.57	467.67	437.15	421.84	386.86	428.25	437.29	448.02	429.93	434.55	25.72
	Peak Velocity Position	72%	74%	73%	74%	72%	71%	72%	74%	72%	75%	73%	1%
Pelvis	Peak to BC (s)	0.200	0.180	0.205	0.175	0.195	0.210	0.200	0.175	0.195	0.180	0.192	0.012
	Peak Velocity (°/s)	240.81	265.76	234.09	223.49	240.54	228.48	267.86	264.02	264.67	262.64	249.24	16.51
	Peak Velocity Position	75%	76%	75%	76%	74%	73%	74%	76%	74%	77%	75%	1%
Thorax	Peak to BC (s)	0.180	0.165	0.185	0.165	0.180	0.195	0.185	0.165	0.180	0.165	0.177	0.010
	Peak Velocity (m/s)	22.68	23.10	22.84	22.90	22.99	22.54	22.65	22.87	22.97	23.03	22.86	0.17
	Peak Velocity Position	78%	79%	79%	80%	78%	76%	77%	80%	78%	80%	79%	1%
Foot	Peak to BC (s)	0.155	0.145	0.160	0.135	0.155	0.170	0.165	0.140	0.155	0.140	0.152	0.011

Table A47: The timing of the different phases present in a rugby goal kick (Participant 10)

		K1	**K2**	**K3**	**K4**	**K5**	**K6**	**K7**	**K8**	**K9**	**K10**	**Mean**	**STD**
Max Knee Flexion	Angle	119.25	125.49	124.51	126.69	123.01	118.67	125.49	124.55	125.89	123.61	123.72	2.59
	Position	69%	70%	70%	70%	69%	67%	68%	70%	69%	71%	69%	1%
Max Hip Flexion	Angle	-25.80	-27.44	-27.59	-24.62	-26.82	-26.73	-27.56	-26.55	-27.93	-26.37	-26.74	0.94
	Position	59%	60%	59%	59%	59%	57%	57%	59%	58%	61%	59%	1%

Table A48: The length of the final stride before ball contact (Participant 10)

	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
Distance of Launch (m)	1.496	1.536	1.559	1.438	1.483	1.487	1.480	1.518	1.498	1.506	1.500	0.031

Table A49: The key events during the goal kick (Participant 10)

	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
S1/K1	0	0	0	0	0	0	0	0	0	0	0%	0%
K2	42%	41%	42%	41%	40%	39%	38%	41%	40%	43%	41%	1%
S2	59%	60%	61%	60%	59%	56%	57%	60%	58%	62%	59%	2%
K3	79%	81%	79%	81%	79%	77%	78%	81%	79%	82%	80%	2%
S3	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	0%

Table A50: The magnitude and position of maximum knee and hip flexion (Participant 10)

	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
S1/K1 to K2	0.300	0.285	0.315	0.280	0.285	0.280	0.270	0.280	0.280	0.310	0.289	0.015
K2 to S2	0.125	0.130	0.140	0.130	0.130	0.120	0.135	0.130	0.130	0.130	0.130	0.005
S2 to K3	0.140	0.145	0.140	0.145	0.145	0.150	0.145	0.145	0.145	0.145	0.145	0.003
K3 to S3	0.150	0.135	0.155	0.130	0.145	0.165	0.155	0.130	0.150	0.130	0.145	0.013
Whole Kick	0.715	0.695	0.75	0.685	0.705	0.715	0.705	0.685	0.705	0.715	0.708	0.019

Participant 11

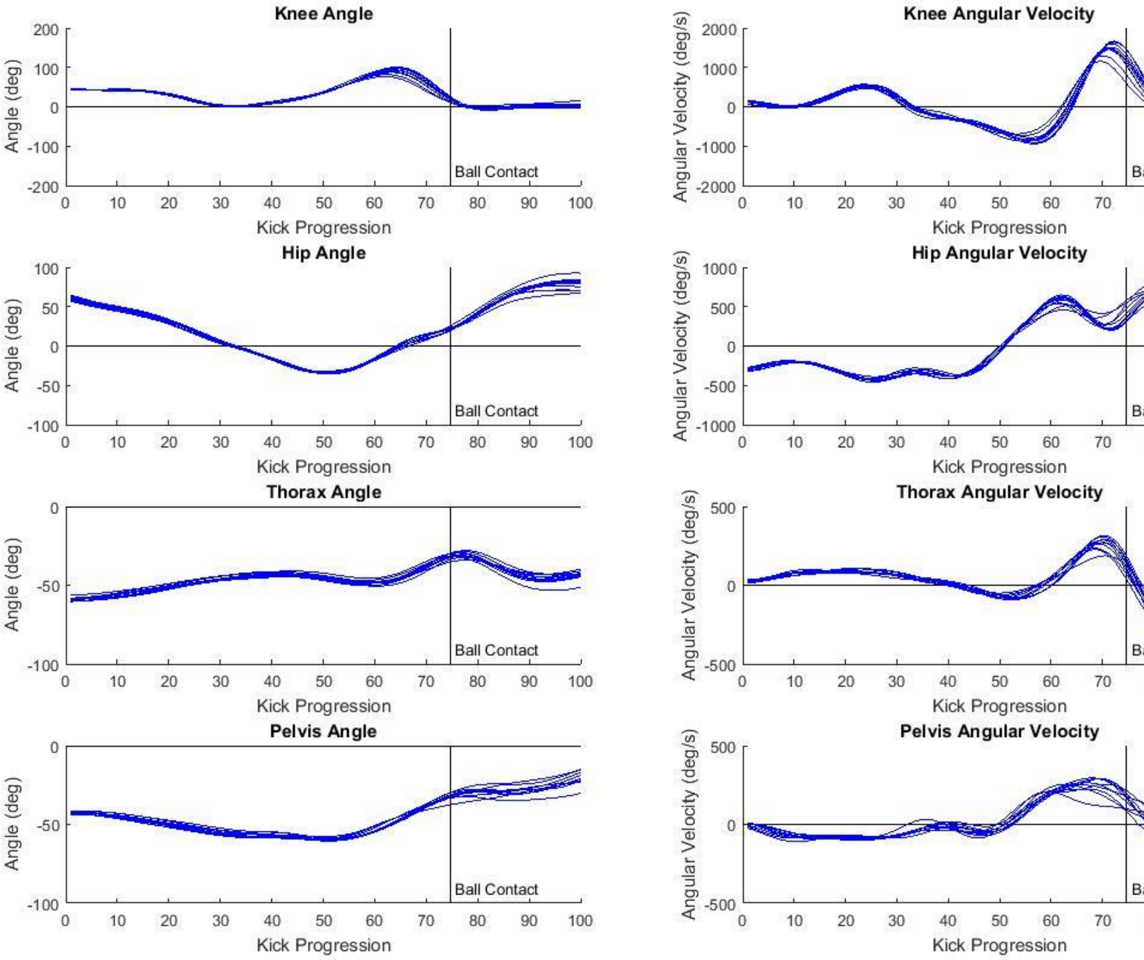

Figure A 11: Joint kinematics of Participant 11

Table A51: Peak velocities, along with the position at which they occur

(Participant 11)

		K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
Knee	Peak Velocity (°/s)	1461.46	1509.72	1293.78	1597.68	1669.29	1494.28	1457.03	1483.77	1638.30	1151.93	1475.72	147.93
	Peak Velocity Position	70%	71%	70%	68%	70%	69%	68%	68%	69%	68%	69%	1%
	Peak to BC (s)	0.205	0.190	0.195	0.220	0.195	0.205	0.215	0.215	0.205	0.210	0.206	0.009
Hip	Peak Velocity (°/s)	608.83	592.02	580.27	626.55	649.68	586.09	544.53	538.48	625.54	547.14	589.91	36.32
	Peak Velocity Position	61%	62%	75%	59%	60%	61%	59%	59%	59%	73%	63%	6%
	Peak to BC (s)	0.265	0.250	0.165	0.280	0.260	0.260	0.270	0.275	0.270	0.180	0.248	0.038

	Peak Velocity (°/s)	255.75	290.64	252.50	294.95	287.79	224.08	251.15	265.59	291.74	209.21	262.34	28.18
	Peak Velocity Position	69%	69%	63%	65%	67%	65%	62%	64%	66%	59%	65%	3%
Pelvis	Peak to BC (s)	0.210	0.200	0.240	0.240	0.215	0.235	0.250	0.240	0.225	0.275	0.233	0.021
	Peak Velocity (°/s)	235.08	279.95	263.34	314.11	290.11	226.64	271.28	288.85	308.58	187.53	266.55	37.58
	Peak Velocity Position	67%	69%	69%	67%	68%	66%	67%	67%	67%	69%	68%	1%
Thorax	Peak to BC (s)	0.225	0.205	0.200	0.225	0.205	0.225	0.220	0.220	0.220	0.205	0.215	0.009
	Peak Velocity (m/s)	19.97	19.74	19.61	20.46	21.25	20.57	20.37	20.84	21.51	18.74	20.31	0.78
	Peak Velocity Position	72%	74%	74%	70%	72%	72%	71%	71%	71%	71%	72%	1%
Foot	Peak to BC (s)	0.190	0.170	0.170	0.205	0.180	0.190	0.190	0.195	0.190	0.190	0.187	0.010

Table A52: The timing of the different phases present in a rugby goal kick (Participant 11)

		K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
Max Knee Flexion	Angle	92.29	93.75	81.74	96.98	99.03	95.13	87.28	89.27	100.88	76.41	91.28	7.34
	Position	62%	63%	62%	61%	62%	61%	61%	61%	62%	61%	62%	1%
Max Hip Flexion	Angle	-33.61	-33.75	-33.68	-33.85	-35.58	-34.47	-34.69	-34.67	-34.48	-32.31	-34.11	0.84
	Position	50%	50%	51%	49%	49%	49%	49%	49%	49%	50%	50%	1%

Table A53: The length of the final stride before ball contact (Participant 11)

	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
Distance of Launch (m)	1.523	1.526	1.516	1.527	1.545	1.519	1.515	1.541	1.504	1.474	1.519	0.019

Table A54: The key events during the goal kick (Participant 11)

	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
S1/K1	0	0	0	0	0	0	0	0	0	0	0%	0%
K2	28%	28%	28%	28%	26%	28%	27%	31%	27%	29%	28%	1%
S2	50%	50%	51%	50%	50%	49%	49%	49%	50%	49%	50%	1%
K3	73%	74%	75%	71%	72%	72%	71%	72%	71%	73%	72%	1%
S3	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	0%

Table A55: The magnitude and position of maximum knee and hip flexion (Participant 11)

	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
S1/K1 to K2	0.190	0.185	0.180	0.195	0.170	0.185	0.180	0.205	0.180	0.190	0.186	0.010
K2 to S2	0.145	0.145	0.150	0.145	0.155	0.145	0.145	0.125	0.150	0.135	0.144	0.008
S2 to K3	0.155	0.155	0.155	0.145	0.145	0.155	0.150	0.150	0.145	0.160	0.152	0.005
K3 to S3	0.185	0.170	0.165	0.200	0.180	0.185	0.190	0.190	0.190	0.180	0.184	0.010
Whole Kick	0.675	0.655	0.65	0.685	0.65	0.67	0.665	0.67	0.665	0.665	0.665	0.011

Participant 12

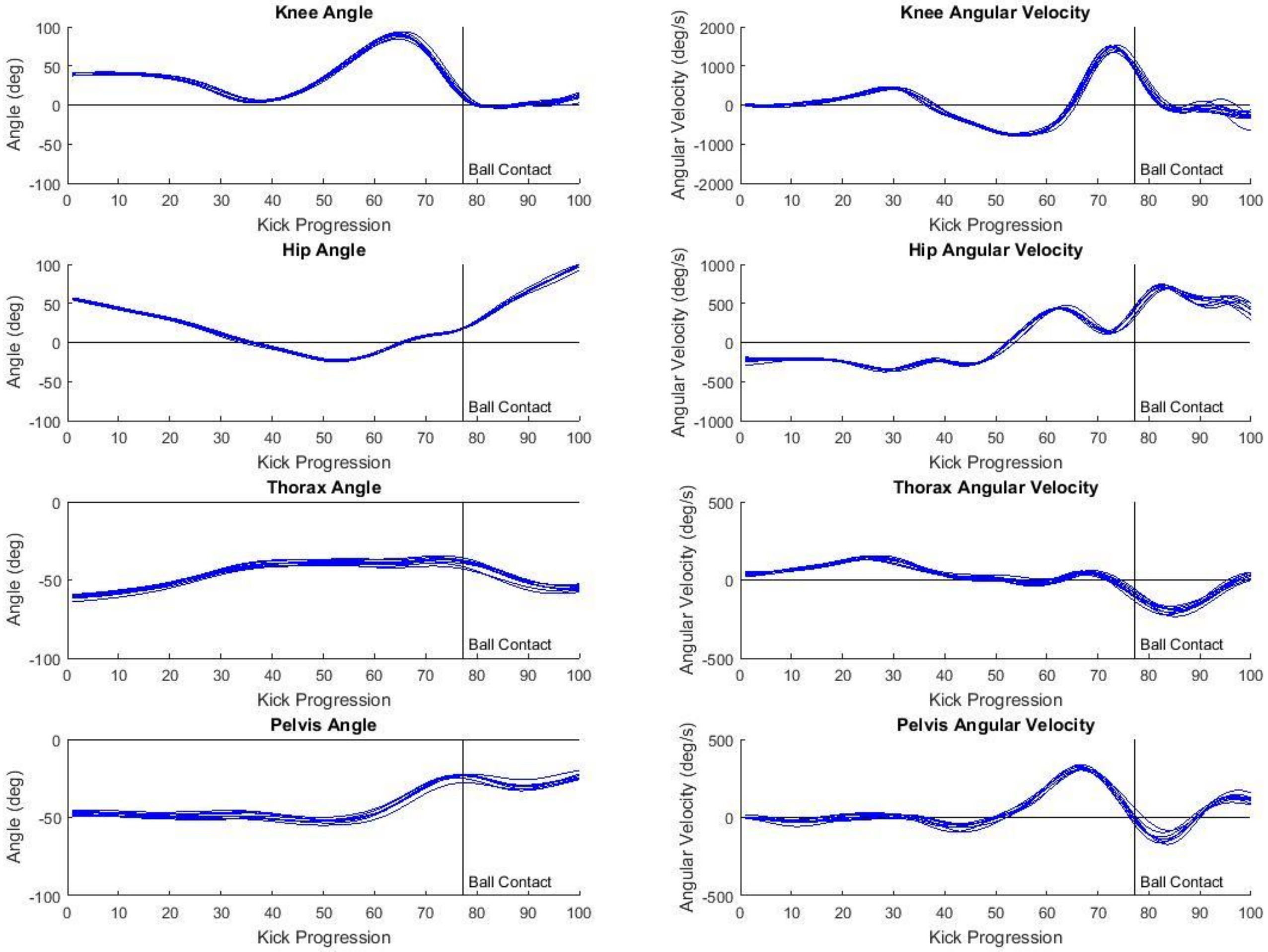

Figure A12: Joint kinematics of Participant 12

Table A56: Peak velocities, along with the position at which they occur (Participant 12)

		K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
Knee	Peak Velocity (°/s)	1473.71	1517.13	1349.38	1426.55	1369.19	1498.38	1480.36	1498.39	1521.86	1512.71	1464.77	58.99
	Peak Velocity Position	71%	69%	71%	69%	70%	70%	71%	71%	72%	70%	70%	1%
	Peak to BC (s)	0.190	0.200	0.190	0.205	0.195	0.195	0.190	0.185	0.185	0.195	0.193	0.006
Hip	Peak Velocity (°/s)	429.94	440.26	427.91	376.98	403.82	450.56	437.67	426.55	474.50	448.09	431.63	25.26
	Peak Velocity Position	61%	60%	61%	59%	60%	61%	62%	60%	62%	60%	61%	1%
	Peak to BC (s)	0.255	0.265	0.255	0.270	0.260	0.260	0.250	0.250	0.245	0.255	0.257	0.007
Pelvis	Peak Velocity (°/s)	305.95	338.99	314.38	320.69	325.50	321.88	302.44	328.25	309.31	303.31	317.07	11.43
	Peak Velocity Position	65%	64%	65%	64%	65%	64%	65%	64%	66%	64%	65%	1%
	Peak to BC (s)	0.230	0.235	0.230	0.235	0.225	0.235	0.230	0.225	0.220	0.230	0.230	0.005
Thorax	Peak Velocity (°/s)	59.75	54.86	30.61	40.71	42.84	52.85	44.51	57.65	49.92	44.77	47.85	8.43
	Peak Velocity Position	66%	65%	65%	63%	66%	66%	66%	65%	67%	65%	66%	1%
	Peak to BC (s)	0.220	0.230	0.225	0.240	0.220	0.225	0.220	0.220	0.215	0.225	0.224	0.007
Foot	Peak Velocity (m/s)	20.19	21.14	20.63	20.46	20.08	20.67	20.44	21.10	20.26	20.88	20.58	0.35
	Peak Velocity Position	71%	70%	71%	69%	70%	70%	71%	71%	72%	70%	71%	1%
	Peak to BC (s)	0.190	0.195	0.190	0.205	0.195	0.195	0.190	0.180	0.185	0.190	0.192	0.006

Table A57: The timing of the different phases present in a rugby goal kick (Participant 12)

		K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
Max Knee Flexion	Angle	89.52	92.16	84.22	86.87	87.13	93.19	89.31	90.80	93.80	91.49	89.85	2.90

	Position	63%	62%	62%	61%	62%	63%	63%	63%	65%	62%	63%	1%
Max Hip Flexion	Angle	-21.82	-23.93	-22.34	-22.31	-22.12	-22.35	-23.00	-23.37	-22.66	-24.67	-22.86	0.85
	Position	52%	50%	52%	50%	51%	52%	53%	51%	53%	51%	51%	1%

Table A58: The length of the final stride before ball contact (Participant 12

	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
Distance of Launch (m)	1.562	1.582	1.611	1.583	1.607	1.566	1.608	1.609	1.583	1.598	1.591	0.017

Table A59: The key events during the goal kick (Participant 12)

	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
S1/K1	0	0	0	0	0	0	0	0	0	0	0%	0%
K2	36%	35%	35%	34%	35%	36%	37%	34%	36%	34%	35%	1%
S2	53%	53%	54%	52%	54%	53%	54%	53%	55%	52%	53%	1%
K3	75%	74%	75%	73%	74%	74%	75%	75%	75%	74%	74%	1%
S3	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	0%

Table A60: The magnitude and position of maximum knee and hip flexion (Participant 12)

	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Mean	STD
S1/K1 to K2	0.235	0.230	0.230	0.220	0.230	0.235	0.240	0.215	0.235	0.215	0.229	0.009
K2 to S2	0.110	0.115	0.120	0.120	0.120	0.115	0.115	0.120	0.120	0.115	0.117	0.003
S2 to K3	0.145	0.140	0.135	0.135	0.130	0.140	0.135	0.140	0.135	0.145	0.138	0.005
K3 to S3	0.165	0.170	0.165	0.180	0.170	0.170	0.165	0.155	0.160	0.165	0.167	0.007
Whole Kick	0.655	0.655	0.65	0.655	0.65	0.66	0.655	0.63	0.65	0.64	0.650	0.009