Knee Joint Competence Post Anterior Cruciate Ligament Reconstruction in Amateur South Western Districts Rugby Players

Master protocol submitted to:
Nelson Mandela University

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DECLARATION:

In accordance with Rule G4.6.3, I hereby declare that the above-mentioned master's degree is my own work, and that it has not previously been submitted for assessment to another university, or for another qualification.

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STUDENT CONTRIBUTION

The dissertation was completed in fulfilment of the degree of Master of Human Movement Science (Research) in the Faculty of Health Sciences at the Nelson Mandela University.

Assistance was sought from Dr Wilbert Sibanda for statistical guidance.

The final dissertation was sent for language editing prior to final submission for examination, allude to certificate as Appendix I.

GRANTS & FUNDING

The table below provides a budgetary guideline cost incurred during the study. The Sport Science Scholarship has been awarded for the year 2021 to the value of R10 000.

BUDGET

INCOME	Funding (2021 Sport Science)	R10 000.00	
	Total Income		**R 10 000.00**
EXPENSES	Language editor	R2 000.00	
	Computer and internet usage	R12 000 (R500x 24 months)	
	Telecommunication costs	R3 000.00	
	Stationery and printing	R1 500.00	
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	Total expenses		**R38 500.00**

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ABSTRACT

Background: Globally, literature has shown that rugby players struggle to return to the same level of performance post anterior cruciate ligament (ACL) reconstruction. This phenomenon is further exacerbated amongst South African Rugby players, compounded by the ranking of the national team amongst the top ten rugby teams worldwide. Paired with the psychosocial aspect of return to play, the physical and physiological competence of the knee joint is of pivotal importance.

Purpose: To compare relative dynamic stability scores paired with electromyography (EMG) scores between the injured and uninjured legs, thereby enabling an explorative, descriptive report on dynamic proprioceptive abilities post ACL reconstruction (ACLR). The study findings therefore aim to inform rehabilitative practice in a rugby player who underwent ACLR.

Study Design: A quantitative, explorative and descriptive design was used, with a purposive sampling strategy.

Methods: Biographical and anthropometrical data was measured upon inception. Muscular activation was measured using electromyography (EMG) placements on quadriceps muscles which included the *vastus medialis obliques (VMO),* and *vastus lateralis (VL)*. Dynamic proprioception was measured using the star excursion balance test (SEBT) and normalised to leg length. A neuromuscular fatigue protocol was used to measure the impact of neuromuscular fatigue on dynamic stability, and muscle activation between the injured and uninjured lower limbs.

Results: A sample of 15 participants from the South Western Districts (SWD) rugby team, fitting the inclusion criteria, were included in the study. The average age was 27±2.7 years. The results indicated that fatigue did not significantly affect the SEBT scores between the injured and uninjured lower limbs. However, the VMO muscle activation showed a statistically significant difference in muscle firing in a pre-fatigue state. This difference was evident in two of the eight directions namely anteromedial direction ($p = 0.041$), and in the lateral direction ($p = 0.047$). Furthermore, these result differences were favoured in the uninjured limb. No significant differences between the injured and uninjured lower limbs were found in respect to VMO and VL muscle activation, in a fatigued state.

Conclusion: Practically translated, the study results showed that the injured lower limb, showed no significant differences in dynamic stability during both the non-fatigued and the fatigued SEBT. Therefore, the finding of this study is a steppingstone towards informing return to play criteria for adequate dynamic knee stability and proprioception. It should be noted that further research is necessary to refine return to play criteria and thereby decrease the risk for re-injury.

Keywords: anterior cruciate ligament; dynamic stability; neuro-muscular fatigue; reconstruction; re-injury; return-to-sport; rugby.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ACL – Anterior Cruciate Ligament

ACLR – Anterior Cruciate Ligament Reconstruction

ANOVA – Analysis of Variance

ATP – Adenosine triphosphate

CI – Confidence Interval

CNS – Central Nervous System

EMG – Electromyography

LEMF – Lower Extremity Muscular Fatigue

NMF – Neuromuscular Fatigue

p – P Value (statistical significance)

SD – Standard Deviation

SEBT – Star Excursion Balance Test

SWD – South Western Districts

t – t-statistic

VL – *Vastus lateralis*

VMO – *Vastus medialis obliques*

µV – Micro Volts

95%CI – 95% Confidence Interval

CHAPTER 1

OVERVIEW OF THE STUDY

1.1 INTRODUCTION

This chapter provides an overview of the study. Knee joint competence has been defined by Abulhasan and Grey (2017:34) as the proprioceptive mechanism that protects the integrity of the knee joint after ACL injury. The chapter therefore begins with outlining a brief literature review and contextualisation of rugby and ACL injuries as has been evident in literature. This is followed by the research premise, aim and objectives. Prior to outlining the study significance, a brief concept clarification is provided. The chapter culminates in a chapter summary.

1.2 STUDY BACKGROUND

Non-contact ACL injuries have been a concern in rugby players worldwide, with an estimated five million registered rugby union players in 121 countries (Yeomans, Kenny, Cahalan, Warrington, Harrison, Hayes & Comyns, 2018:837). As contact ACL injuries can rarely be prevented, the risk of non-contact ACL injury can be minimised by understanding how knee kinetics and kinematics change, pre-and post-fatigue status (Bourne, Opar, Williams & Shield, 2015:2663).

Rugby is one of the top three South African sporting codes, participating at both competitive and recreational levels (Brown, Verhagen, Knol, Van Mechelen & Lambert 2016:221). South Africa has 121 663 registered adult rugby players. Currently the national rugby team is ranked first globally, despite not having placed under the top seven of World Rugby rankings since 2003 (World Rugby, 2020:1). World Rugby (2020:1) ranks a South African rugby player as the most competitive in the world. Due to the nature of the sport, together with the ranking of the sport, rugby related injuries are common (Bourne, Opar, Williams & Shield, 2015:2663).

Literature published on South African rugby players indicated an injury rate for senior professional male rugby players of 81 injuries per 1000 player hours, which has been compared to a 26.7 injuries per 1000 player hours incident rate in youth and adolescent rugby players, indicating a 54 percent higher injury rate in senior rugby players when compared to adolescent rugby players (Williams, Trewartha, Kemp & Stokes, 2013:1043). Fuller, Taylor, Kemp and Raftery (2017:51) reported that the injury rate in players between the 2011 and the 2015 Rugby World Cup increased, but not significantly so. Contradictory to this, literature published by Starling, Readhead, Viljoen and Lambert, (2020:11) reported a decrease in injured players during the local Currie Cup tournaments from 93 in 2017 to 66 in 2018 (Starling *et al*., 2020:11). However, the reported injury rate for South African rugby players with the focus on time-loss injuries (82 injuries per 1000 hours exposed) was very similar to that of England (81 injuries per 1000 hours exposed) (Starling *et al*., 2020:14).

The increased rate of overall injury has been classified as “high” compared to non-contact sports such as soccer (12.6 injuries per 1000 player hours) and basketball (11.6 injuries per 1000 player hours), while the increase in injury rate is comparable to other contact sports such as Australian-rules-football and ice hockey (Yeomans *et al*., 2018:837). However, studies noted that amateur rugby injury rates fluctuate between 5.9 injuries per 1000 player hours to 99.5 injuries per 1000 player hours. This is due to unreliable data collection and the use of varied injury definitions (Rass & Puckree, 2014:1346; Farnan, Mahony, Wilson & Gissane, 2013:104). Therefore, an increase in injury definition standardisation could lead to a more reliable global injury parameter. This would define more specific injuries which could improve the method of injury rehabilitation and prevention techniques for lower limb dominated injuries, such as ACL injuries in rugby.

Literature suggests that repeated stretch-shortening movements such as cutting, tackling, jumping, and sprinting elicits fatigue in rugby players (Wiggins, Grandhi, Schneider, Stanfield, Webster & Myer, 2016:1861). An additional intrinsic modifiable risk, and possibly the most important risk factor, is the effect that neuromuscular fatigue has on the competency of the knee joint, specifically the ACL (Staiano, Bosio, de Morree, Rampinini & Marcora, 2018:175). Chappel, Herman, Knight, Kirkendall, Garrett and Yu (2005:1022) concluded that after inducing fatigue on the lower legs, fatigued athletes showed altered motor control strategies, indicating that there are large amounts of strain on the ACL, increasing the anterior tibial shear force and overall risk of non-contact ACL injuries.

Literature indicates that the lower limb injuries dominated the injury site, constituting 40 - 56 percent of all injuries (Fuller *et al*., 2017:51; Murphy, Roe, Gissane & Blake, 2018:982). The knee is the most prevalent injury location, with the incidence rate ranging between 14 - 16 percent, followed by posterior thigh injuries ranging between 9.8 - 10.4 percent (Fuller *et al*., 2017:51; Murphy, Roe, Gissane & Blake, 2018:982). In addition, an analysis of the 2017-2018 South African Currie Cup, revealed that sprained ligaments and muscles have been surpassed by central nervous system (CNS) injuries as being the new, most common injury (Starling *et al*., 2020:14).

Elite rugby federations have reported ligament and tendon injuries as posing challenges to the rehab and return to play for players resulting in future career impacts (Fuller *et al*., 2017:55). The reports indicated that ligament and joint injuries in Rugby Union (RU) squads make up 66 percent of most severe injuries, and this encompasses ACL injuries (Kemp, West, Brooks, Cross, Williams, Anstiss, Smith, Bryan, Henderson & Locke, 2019). Player position statistics indicate that players' backs are ranked as the top three injury sites, causing 815 days of absenteeism during a player's rugby lifespan at competitive levels (Brazier *et al*., 2019). This literature has been a focus point on a worldwide stage, however, is not contextually relevant to most South African cohorts, as soft tissue injuries have been reported to be more prevalent. Starling *et al*., (2020:28), indicated that sprained ligaments were the primary reason for days being absent from participating in any team activities. While the above-mentioned literature provides fundamental ideas linked to injuries in rugby players, there is still a gap in literature about diagnosing risk factors for lower limb injuries involving the ACL and re-injury prevention techniques.

Research conducted on returning to Level I sport after ACL reconstruction, reports that there is a greater than four-fold growth in re-injury rates over two years, with a 40 percent re-injury rate during the first six to nine months (Arundale, Capin, Zarzycki, Smith & Snyder-Mackler, 2018:422). Furthermore, it can be noted that symmetrical *quadriceps* strength alone, significantly reduces the knee re-injury rate post ACL reconstruction (Grindem, Snyder-Mackler, Moksnes, Engebretsen & Risberg, 2016: 804). The importance of restoring muscular strength and correcting the biomechanical frameworks, should be a vital part of the rehabilitation process. The addition of proprioceptive functionality should potentially induce and improve neuro-muscular control and subsequently reduce re-injury risk (Grooms, Appelbaum & Onate, 2015:381; Thomas, Dent, Howatson & Goodall, 2017: 955; Kaeding, Leger-St-Jean & Magnussen, 2017:1).

The etiology of ACL injuries are predominantly contactless, intrinsic factors (Gali, Fadel,Marques, Almeida, Gali, & Faria, 2021:21). However, there are reports of injuries occurring due to external forces from direct impact (Montgomery, Blackburn, Withers, Tierney, Moran & Simms, 2018:995). Non-contact ACL injuries arise from a combination of knee extension with externally applied flexion, internal rotation, and valgus moments (Lanier, Knarr, Stergiou, Snyder-Mackler & Buchanan, 2020; Takahashi, Nagano, Ito, Kido & Okuwaki, 2019:26). Even though hormonal, anatomic, gender and genetic-related factors are some of the factors that are related to injury risk, the primary focus of rehabilitation has been dynamic neuromuscular control, since it is an intrinsic modifiable risk and a prospective predictor of primary and secondary injury (Nagelli & Hewett, 2017:221; Nessler, Denney & Sampley, 2017:281; Onate, Herman, Grooms, Sutton & Wilkerson, 2019:359;). According to Kaeding *et al*., (2017:6), the mechanism of non-contact ACL injury is a loss of neuromuscular control. The nature of the non-contact ACL injury mechanism exemplifies the dynamic role of the central nervous system (CNS) to restore function and avoid ACL re-injury (Diekfuss *et al*., 2020:11).

Empirical evidence appears to confirm the notion that rugby players should be able to return to the same playing level as pre-injury, or even excel further post ACLR (Takazawa *et al*., 2016:55). The non-contact mechanism of injury has repeatedly been associated with a failure to maintain knee neuromuscular control. Neuromuscular control is affected by external variables, involving highly intricate dynamic visual stimulation, movement planning, variable surfaces and positions, hasty decision making, environment relations and unanticipated discomposure (Koga, Nakamae, Shima, Bahr & Krosshaug 2018:333; Leppanen *et al*., 2017:386).

The literature concerning ACL rehabilitation for rugby players has its roots in strength rehabilitation (Andrade, Pereira, van Cingel, Staal & Espregueira-Mendes, 2020:514; Eckenrode, Carey, Sennet & Zgonis, 2017:315; Heckmann, Noyes & Barber-Westin, 2018:505). However, there is an insufficient amount of literature concerning the potential risk factors associated with non-contact ACL injuries at an amateur rugby level (Andrade, Pereira, van Cingel, Staal & Espregueira-Mendes, 2020:514;

Eckenrode, Carey, Sennet & Zgonis, 2017:315; Heckmann, Noyes & Barber-Westin, 2018:505). The foundation of this study is grounded in the three premises as stated by Alentorn-Geli, Meyer, Silvers, Samitier, Romero, Lazaro-Haro and Cugat (2009:705) explaining the potential etiology of non-contact ACL injury. The first assumption is based on quad dominance in causing knee joint stabilisation by pulling the tibia anteriorly to the femur causing shear stress in the ACL. The second the leg dominance premises, which indicates that during athletic responsibilities leg dominance, non-requiring leg dominance and force asymmetry could potentially predispose the ACL to injury. Lastly, the ligament dominance premises, states that ground reaction forces are not sufficiently absorbed by lower limb muscles, therefore placing additional load on ligaments to absorb the external load over a reduced period. The additional dynamic force application on the ligaments and joint structures, results in knee valgus, hip internal rotation, and hip adduction, exposing the integrity of the ACL.

1.3 PROBLEM STATEMENT

It is therefore clear that to return rugby players to the field post ACL reconstruction, an understanding of the kinetics and kinematics in combination of proper proprioceptive training of the knee joint, and how these differ between fatigued and non-fatigued states, are required (Koga, Nakamae, Shima, Bahr & Krosshaug 2018:333). Such knowledge would be of use to the clinician, coach and player in optimising strategies that promote correct movement mechanics of the injured player, and optimising the player's return to the sporting field, while also minimising the potential for re-injury. Considering the above, it can be deduced that proprioception measurements are not only being neglected during the preseason functional movement screening and rehabilitation phases after injury, but also in the return to play protocols (Romero-Franco *et al*., 2014:205; Matthews, Green, Matthews & Swanwick, 2017:118).

Furthermore, while there is information regarding rehabilitative measures that are focussed on the optimisation of the biomechanical-neurological integrated system, there is limited literature that focussed on the sport specific ACL neuro-muscular rehabilitation (Sarah & Oh, 2016:267; Zebis *et al.*, 2017). Therefore, the purpose of this study was to identify the competency of the knee joint post ACL reconstruction, with the focus on neuromuscular control and muscle activation symmetry to gather evidence, considering the three premises. As most of the literature elaborates on rugby injuries in professional players, this study investigates amateur SWD club rugby players to identify relevant re-injury mechanisms.

1.4 RESEARCH PREMISES, AIM AND OBJECTIVES

1.4.1 Research premises

The three premises focal to ACLR can be summarised as:

1. The *quadriceps* dominance premises, which propose that the quadriceps stabilises the knee joint by primarily using the *quadriceps* muscles, which pulls the tibia anteriorly to the femur causing shear stress in the ACL.
2. The leg dominance premises, which indicates that during athletic responsibilities leg dominance, non-requiring leg dominance and force asymmetry could potentially predispose the ACL to injury, and
3. The ligament dominance premises, which states that ground reaction force is not sufficiently absorbed by lower limb muscles, forcing the ligaments to absorb them over a reduced period. This results in an extreme dynamic of knee valgus, hip internal rotation, and hip adduction, exposing the integrity of the ACL.

1.4.2 Research Aim

The aim of this study was to explore, describe and compare knee joint competence of the injured and uninjured lower limb post ACLR in male, amateur SWD rugby players.

1.4.3 Research Objectives

To achieve the above-mentioned aim, the following objectives were set:

- to explore and describe VMO and VL muscle activation between the injured and uninjured lower limb as measured by a dynamic stability test in pre- and post-fatigue status in amateur SWD rugby players,
- to explore and describe proprioception and neuromuscular control using the multidirectional star excursion balance test scores between the injured and uninjured lower limb pre-and post-fatigue in amateur SWD rugby players, and

- to explore and describe knee joint competence by comparing VMO and VL muscle activation and SEBT scores between the injured and uninjured lower limbs, pre- and post-fatigue in amateur SWD rugby players.

1.5 CONCEPT CLARIFICATION

The concepts below are key to the understanding of the study and have been clarified and contextualised within the domain of the study.

1.5.1 Knee Joint Competence

Knee joint competence has been defined by Abulhasan and Grey (2017:34) as the proprioceptive and neuromuscular mechanism that protects the integrity of the knee joint after ACL injury. For this study, knee joint competence will encompass the full definition as outlined by Abulhasan and Grey (2017:34).

1.5.2 Proprioception

Linked to the study, proprioception refers to the ability of the body to perceive its own position in space through a continuous loop of feedback between sensory receptors and the nervous system (Han, Waddington, Adams, Anson & Liu, 2016:81). Therefore, proprioception will entail a dynamic stability test in the form of a multidirectional Star Excursion Balance Test (SEBT).

1.5.3 Anterior Cruciate Ligament Reconstruction (ACLR)

The anterior cruciate ligament is the primary stabiliser of the knee joint. If torn, it can be reconstructed by *hamstring*, *quadriceps,* or *patellofemoral* ligament reconstruction. This is surgically achieved by auto- or allograft (Kecojevic, Hahaji & Ninkovic, 2019). Therefore, for the purpose of this study, ACLR will include both auto and allografts using the *hamstring, quadriceps,* or *patellofemoral* ligament reconstruction techniques.

1.5.4 Neuromuscular fatigue

Neuromuscular fatigue is defined as a transient decrease in maximal voluntary performance capacity of a muscle, accompanied by the metabolic changes, which directly impacts the contractile pathways (Sharma, 2017:13). The definition, as outlined by Sharma (2017:13), was theoretically applied to participants who could no longer reach the 90° single leg squat depth, and/or keep to five metronome beats of 97 Hz during the testing protocol.

1.6 SIGNIFICANCE OF THE STUDY

Anterior cruciate ligament reconstruction has been a major concern world-wide for the athletic and non-athletic communities. Therefore, it is clear that, to return players to the field post ACLR, an understanding of the kinetics and kinematics in combination of proper proprioceptive dynamic stability training of the knee joint, and how these differ between pre-fatigue and post-fatigue states, is required. Such knowledge would be of use to the clinician, coach and player in optimising strategies that promote correct movement mechanics of the injured player, and optimising the player’s return to the sporting field, while potentially also minimising the potential for re-injury. Considering that proprioception measurements are not being neglected during the pre-season functional movement screening, rehabilitation phases after injury and in the return to play protocols, but rather lack specific injured site multidirectional proprioceptive measurements for rugby players. This could also apply to other participants in other sporting codes.

1.7 STRUCTURE AND FORMAT OF DISSERTATION

The structure and format are a vital part of any research study, and it is important to ensure uniformity; therefore, the dissertation followed a specific format. Below is an outline:

- Chapter One: Overview of the study
- Chapter Two: Literature review
- Chapter Three: Research methods and procedures
- Chapter Four: Results
- Chapter Five: Discussion
- Chapter Six: Limitation, recommendations and conclusion

1.8 CHAPTER SUMMARY

This chapter comprises of an overview of the study, highlighting the problem statement, research premises, aim, and objectives. The concepts used in this study were clarified, as well as the structure and format of the study. The next chapter will focus on an in-depth literature review of the factors influencing ACLR re-injury. In addition, literature appraised a gap in literature informing practice on final phase ACLR rehabilitation. The inclusion of neuro-muscular training to improve proprioception of the knee joint integrity in the application of ACLR rehab programme prescription to enhance the probability of return to play is being addressed. The subsequent resultant decreased ACLR re-injury rate in rugby players is mentioned.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

The aim of this study was to explore and describe knee joint competence post ACLR in male amateur SWD rugby players, between the injured and uninjured limbs. Therefore, to place this study into perspective, and to provide background information that will facilitate the discussion or the findings, this chapter provides a review of related literature. This chapter begins by providing an overview of the knee joint demands placed on amateur rugby players, and the need for well-developed knee proprioception to be able to successfully execute cutting and pivoting movements. The chapter begins with an outline of the key anatomical and physiological parameters that are related to ACL injuries, followed by a descriptive review of rugby related injuries. To contextually place ACL injury, the mechanism of injury will be discussed. Finally, this chapter concludes with an exploration of both proprioception and neuromuscular fatigue on ACL injuries and rehabilitation.

2.2 LITERATURE SEARCH STRATEGY

A comprehensive literature study was conducted to appraise available literature for this study. Sources of secondary data included library resources, internet articles, books, journal articles and other appropriate information, with the emphasis being placed on pending discussions and support obtained from peer reviewed academic journals, both locally and internationally published. The secondary data was analysed in terms of purpose, accuracy, credibility, relevance, reliability, and appropriateness in relation to the variables of this study. The study, therefore, utilised academic articles, and was complemented by research reports and articles from orthopaedic rehabilitation and rugby conditioning practitioners in popular press and published journals.

2.3 ANATOMY OF THE KNEE JOINT

The knee joint connects the upper and lower leg, consisting of the proximal tibiofibular joint, patellofemoral joint and surrounding soft tissues (Kecojevic, Hahaji & Ninkovic, 2019). The knee is a complex hinge joint, with the greatest range of motion in flexion and extension about the sagittal plane and valgus, and varus rotation about the frontal plane. The knee joint is positioned between the two longest levers of the body, the femur and tibia. The role of the knee joint makes it prone to injuries and, therefore, by describing and discussing its anatomical features, there would be an improvement in clinical and rehabilitative efficacy (Abulhasan & Grey, 2017:34).

The primary and secondary stabilisers work together to help the knee function abidingly (Abulhasan & Grey, 2017:34). Fig. 2.1 is a diagrammatic illustration of the knee joint. The primary stabilisers are two collateral ligaments, medially and laterally, as well as two even stronger cruciate ligaments, anterior and posterior. There are additional small ligaments that surround the knee and assist in the overall knee stability, which includes the capsular, anterolateral, arcuate, and posterior oblique ligament. Two fibrocartilaginous menisci, medial and lateral, between the medial and lateral femoral condyles and the tibia, provide a frictionless surface to allow joint movement (Abulhasan & Grey, 2017:34). The secondary stabilisers consist of the muscles around the knee, namely the: *quadriceps, hamstrings, gastrocnemius, plantaris, sartorius* and *gracilis*. These muscles also interact with the neuromuscular system to control knee motion, playing an important role in knee proprioception (Abulhasan & Grey, 2017:34).

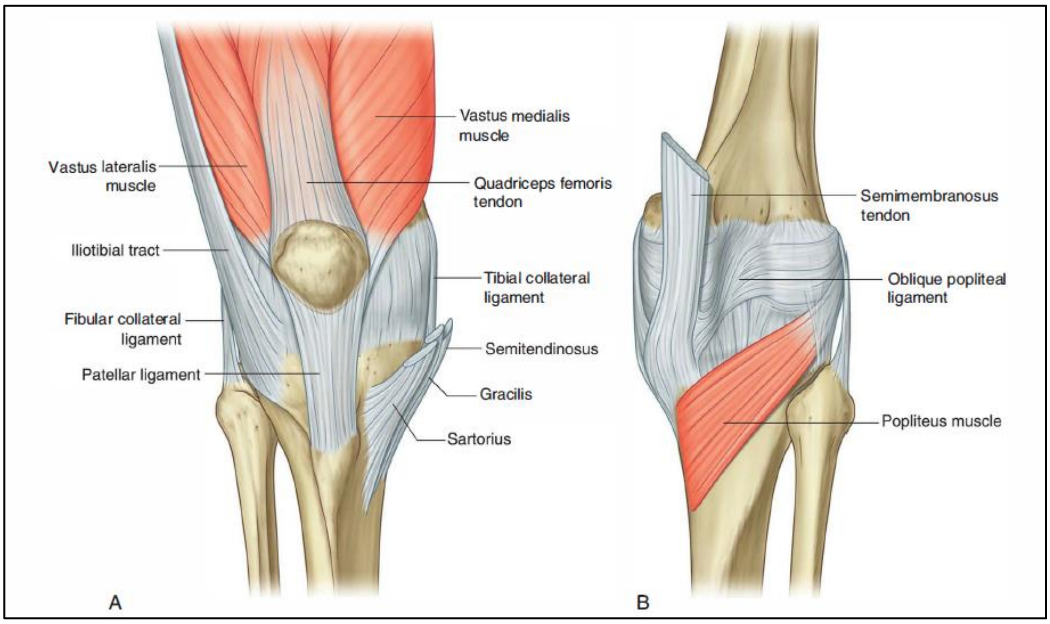

Figure 2.1: Anatomy of A) Anterior aspect of the knee, B) Posterior aspect of the knee (Abulhasan & Grey, 2017:34).

The *hamstring* muscles originate from the ischial tuberosity and insert over the knee joint onto the tibia and fibula. The *hamstring* is responsible for knee flexion, tibial rotation, and the limitation of anterior tibial translation to the femur which, in essence, protects and assists the ACL (Petersen & Tillmann, 2002:710). The four *quadriceps* muscles all insert across the anterior aspect of the knee joint onto the tibial tuberosity via the patella. The *quadriceps* extend the knee joint and limit the amount of posterior tibial translation to the femur, which assists in dynamic secondary knee stability together with the primary stabilising cruciate ligaments (Abulhasan & Grey, 2017:32). The lateral condyle of the femur serves as the origin for the *popliteus* muscle that inserts onto the posterior surface of the tibia. The *popliteus* muscle is responsible for the prevention of anterior dislocation of the femur, unlocking the knee joint to allow flexion, and lateral rotation of the femur on the tibia if the tibia is fixed (standing), as well as medial rotation of the tibia on the femur if the femur is fixed (sitting) (Abulhasan & Grey, 2017:32).

In addition to the stabilising tendons, ligaments and musculature, a dual-layered structure surrounding the knee joint, the knee capsule, plays a vital role in knee joint stability and mobility. The capsule is thinner anteriorly, which thickens with the collateral ligaments as it stretches posteriorly. The superficial layer of the knee capsule is comprised of fibrous connective tissue that stabilises the knee joint, whereas the deeper layer is comprised of a synovial membrane secreting synovial fluid into the joint to provide lubrication (Goyal, Singla & Paul, 2018).

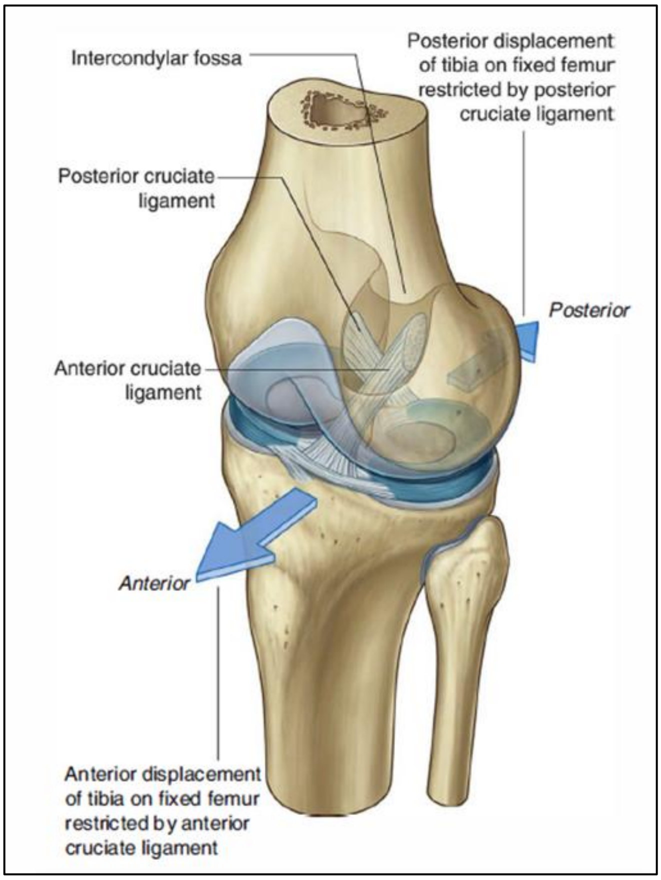

Figure 2.2: Functional anatomy of an ACL (Abulhasan & Grey, 2017:34).

The focus of this study is centred around a specific ligament within the knee joint known as the anterior cruciate ligament (ACL). The superior lateral view of the knee joint as indicated by Figure 2.2., displays the anatomical positioning of the ACL. The ACL is the key stabiliser of the knee joint, contributing to 85 percent of knee stabilisation and, as a result, it is the most frequently injured (Abulhasan & Grey, 2017:34). The ACL provides stability by resisting hyperextension, anterior tibial translation, and rotational loads, which is the main function of the ACL (Duthon, Barea, Abrassart, Fasel, Fritschy and Menetrey, 2006:204). The ACL originates from the femur, slightly posterior to the medial surface of the lateral condyle, and inserts onto the tibia, at the anterior of the intercondylar region (Petersen *et al*., 2002:710).

The ACL ranges from 25 – 35 mm in length, nearly 10 mm in breadth and is 4-10 mm wide. It is roughly triangular in cross-section, and tapers along its length from both ends up to the midsection (Marieswaran, Jain, Garg, Sharma & Kalyanasundaram, 2018:2). Branches of the genicular artery, which consists of the anteromedial and posterolateral bundles, supply the ACL. The shortest band is formed by the anteromedial bundle, and is tight in flexion and relaxed in extension, while the posterolateral bundle is lax in flexion and tense in extension. Between 20 – 30 degrees under regular knee motion, the ACL experiences the least strain (Kang, Koh, Lee & Chun, 2020:19).

The tibial nerve innervates the ACL, and has three mechanoreceptors and nerve endings, each with a specific function. There is one Pacinian receptor, which signals motion, and two Ruffini receptors which sub-assist speed and acceleration, which are very sensitive to stretching (Schutte, Dabezies, Zimny & Happel, 1987:243). Furthermore, a small number of free nerve endings have been identified in the ACL that are responsible for pain (Abulhasan & Grey, 2017:35). The indicators associated with muscle length, derives from the tension fluctuations carried by the Group Ia, Ib and II of the type A nerve fibres from the primary nerve endings in the muscle spindle, as well as the Golgi tendon organs in the muscle tendon to the spinal cord through the dorsal root ganglia (Kang, Koh, Lee & Chun, 2020:21. These terminate in the Clarke's column in Rexed's lamina of the lumbar and thoracic spinal cord segments.

Knee stabilisation is divided into two groups namely primary and secondary stabilisers where primary stabilisers consist of the internal ligament such as the ACL and the secondary stabilisers consist of the muscles crossing the knee joint such as the *quadriceps.* The evaluation of the physiological variables, as a possible link to ACL injuries in rugby players, would be incomplete without an in-depth review of the physiological demand's the game of rugby places on the player.

2.4 PHYSIOLOGICAL VARIABLES IN A RUGBY PLAYER

Given the physical and physiological demands during the game of rugby, the detailed physical preparation should complement the degree to which each fitness component is relied on in competition (Vaz, Goncalves, Figueira & Garcia, 2016:78). Key physiological concepts under review below are heart rate responses (HRR) and energy expenditure through interval training and endurance running linked with velocity driven contact.

During a match, players complete intervals of higher-intensity activity such as sprinting and high-speed running, separated by short stretches of lower-intensity activities such as standing, walking, and jogging (Till, Cobley, Morley, O'hara, Chapman & Cooke, 2016:1240). In addition to the frequent bouts between high and low intensity activity, players also engage in frequent physical demanding impacts and wrestling bouts (Johnston, Gabbett & Jenkins, 2014:1088; Austin, Gabbett & Jenkins, 2011:1898). Significantly, more distance at a high speed were covered by inside, outside backs and loose forwards, than other positions (Lindsay, Draper, Lewis, Gieseg & Gill, 2015:485). The total of impacts per minute of match time, as well as the distance covered, is position dependent (Austin, Gabbett & Jenkins, 2011:1898).

Even though the players tend to vary between high and low bouts of intensity throughout the match, the players tend to spend 40 percent of the game at an average of 80 percent of their heart rate max, contextualising rugby as being a physiologically demanding game with no significant differences between forwards and backs (Dubois, Paillard, Lyons, McGrath, Maurelli & Prioux, 2017:85). Heart rate monitoring has been a focus point used in studies to analyse physiological demands in rugby. Therefore, coaches and players should better understand and estimate the metabolic demands during a rugby game by using heart rate-based methods (Dubois, Paillard, Lyons, McGrath, Maurelli & Prioux, 2017:84). It should, therefore, be considered that metabolic conditioning should consist of a mixture between high intensity interval training, and strength training, during the pre- and in-season period.

Correspondingly, in the variety of running bouts between the different positions of the players, there is a difference in the estimated energy expenditure, ranging between 24.7– 40.0 kJ.kg^{-1}, with the backs having the higher range of energy expenditure (Cumins, Gray, Shorter, Halaki & Orr, 2018:3447). Players who stayed longer on the field and spent more time in the high-speed intensity zones (>20 km.h^{-1}), had a higher energy expenditure than players who stayed on the field for a shorter time and spent less time in the high-intensity zone (Cumins, Gray, Shorter, Halaki & Orr, 2018:3448). During training and match play, collision-based activities have a high energy cost when compared to non-contact team sports such as soccer, rugby is associated with notable energy expenditures (Smith, King, Duckworth, Sutton, Preston, O'Hara & Jones, 2018:647).

In support of the literature above, Costello *et al*., (2018:1170), explains that the large amount of energy expenditure of contact-sport athletes appears to exceed kinematic preparation. The afore advocates that nurturing contact-sport athletes appropriately to counter the muscular damage on a micro level with the kinematic workload, is of significant value. However, criterion data of energy expenditure is deficient in all forms of rugby research and has no link to lower limb injury to date (Dubois, Paillard, Lyons, McGrath, Maurelli & Prioux, 2017:84).

During the course of a rugby match, consisting of 80 stop-start minutes, players tend to cover anywhere between 4-8 km, depending on their position, where backs tend to cover more distance compared to forwards (Kempton, Sirotic, Rampinini & Coutts, 2015:24). During this time, the players make a lot of contact with the opposition during attack and defensive set pieces. Tackling is associated with the biggest percentage of injuries (36% of 645 injuries), as it involves high-speed collisions between the players (Seminati, Cazzola, Preatoni & Trewartha, 2017:58). The most common injuries for the tackler are concussion, cervical burner/stinger, brachial plexus burner/stinger or, *quadricep* hematoma.

According to Kempton, Sirotic, Rampinini and Coutts (2015:24), the nature of the sport and physiological demands predisposes the player to an accelerated injury profile. This then leads to an investigation on the rugby injury related facilitators as discussed in the next section.

2.5 FACILITATORS TO RUGBY RELATED INJURIES

Any discussion on the injury profile of rugby players should include the mechanism of injury, the role of footwear, and the playing surface as contributing or facilitating factors (Chavarro-Nieto, Beaven, Gill & Hebert-Losier, 2021:20.

In rugby, where the main purpose is to enter the opponent’s territory to score points, victory relies on the ability of a player to overpower the opponent in contact or, through rapid directional changes (cutting and pivoting), be it to prevent attacking movements, or to avoid defenders (Barnett, Lai, Veldman, Hardy, Cliff, Morgan, Zask, Lubans, Shultz, Ridgers & Rush, 2016:1663). However, the concern is that the most time lost, in a season, is not due to contact related injuries, but rather due to non-contact injuries (Lanier *et al*., 2020; Takahashi *et al*., 2019:26). Hence, it is important that the players have adequate strength, stability, mobility, and proprioceptive abilities to counter any unwanted shear force, varus/valgum moments, rotation, or translation in the lower limb joints, keeping in mind that the knee is the most severe non-contact injury site (Schreurs, Benjaminse & Lemmink, 2017:144).

The results of the study of Sánchez-Sánchez, Gallardo-Guerrero, García-Gallart, Sánchez-Sáez, Felipe, and Encarnación-Martínez (2019:9), indicated that the changes in sport playing surfaces and footwear, are key variables linked with increased injury risk in rugby players. Mainly, three playing surfaces are used in rugby: natural turf, third-generation artificial turf, and a most recent combination of natural and artificial turf (Carden, Bru, Jones & Dixon, 2017:134). Studies have shown the significant impact of the playing turf on rugby injuries (Sánchez-Sánchez *et al*., 2019:9), while other studies have found no significant differences in the overall injury risk between grass and artificial turf, taking match exposure and training sessions into consideration. In being safe with regards to traumatic injuries, however, artificial turf seems to be a risk factor for overuse injuries (Lanzetti, Lupariello, Venditto, Rota, Guzzini, Vadala, Rota & Ferreti, 2017:180).

Furthermore, to lessen the mechanical characteristics of the playing surfaces, players will often adjust rugby boot stud length (Sun, Gu, Mei & Baker, 2017:30). In some cases, this has led to different ground reaction forces due to the type of turf, and the unfamiliar patterns between the length of the practice and playing stud length, potentially altering the proprioceptive abilities of the player (Carden, Bru, Jones & Dixon, 2017:134). Longer studs would provide more grip to improve performance during the execution of cutting or pivoting manoeuvres, but increased traction may lead to a significantly increased knee abduction moments, which will increase the risk of ACL injury (Sun, Gu, Mei & Baker, 2017:32). In summary, the increased ground reaction force, paired with directional changes at high velocity running and fatigued endurance states in rugby, are key facilitators for injury, as well as return to play criteria.

2.6 REVIEW OF RUGBY INJURIES

With the high rate of injuries in rugby, it is crucial to discuss the severity and the time away from rugby due to the injury. A review on the type of injuries and the secondary consequences due to an injury follows in order to establish what methods are currently being used to decrease the number of injuries in rugby or at least decrease the time away from rugby after injury. A study, during the 2015 Rugby World Cup, recorded an incidence of match injuries as being 90.1 match injuries per 1000 player match hours, and 1.0 training injuries per 1000 player training hours (Fuller *et al*., 2017:51). The mean severity of injuries was 29.8 days absence from matches, with the backs (30.4 days absence) having slightly more days absent than the forwards (29.1 days absence) (Viviers, Viljoen & Derman, 2018:224 and Fuller, Taylor, Kemp & Raftery, 2017:52).

The high injury rate in rugby has negatively influenced competitive success (Brazier *et al*., 2019:138). When assessing time loss from injury and team success in elite rugby teams, literature found clear negative associations between injury burden and team success (King, Hume Gissane & Clark, 2017:197). There are multiple types of risk management models available (Williams, Trewartha, Kemp, Brooks, Fuller, Taylor, Cross & Stokes, 2016:651). An integrated approach to the risk areas, enables doctors, physiotherapists, and all forms of coaching staff to assess and adjust away from risk areas accordingly, with the focus on current practices with regard to injury prevention, rehabilitation, and treatment (Brazier, Antrobus, Stebbings, Day, Hefferman, Cross & Williams, 2019:138).

The reduction in the occurrence and severity of injuries could lead to a greater seasonal and overall team success (Hulin, Gabbet Lawson, Caputi & Sampson, 2016:231). Due to the nature of rugby, where high impact contact regularly occurs through numerous tackles and physical collisions, injuries are common (Brazier *et al*., 2019:138). Ligamentous knee injuries are common, and often lead to joint instability, damage to other ligaments, articular cartilage, and menisci, as well as the early onset of osteoporosis (Alazzawi, Sukeik, Ibrahim & Haddad, 2016:222). A loss of proprioception following an ACL injury has been well documented (Arockiaraj, Korula, Oommen, Devasahayam, Wankhar, Velkumar & Poonnoose, 2013:188). A review of rugby injuries, and injury profiling for elite vs amateur rugby players as well as ACLR rates in rugby players, are summarised in a literature review in the section below.

Since contact injuries have affected slightly over 80% of all rugby players, it has previously been assumed that contact injuries are unavoidable (Cross, Kemp, Smith, Trewartha & Stokes, 2016:926). Being tackled caused 25 percent of all injuries, making it the most common injury event during matches (King *et al*., 2017:197). However, several other causes of injuries include, but are not limited to scrums, rucks, mauls, tripping, twisting, slipping, falling, overuse and overexertion (Brazier *et al*., 2019:138). Of all injuries, concussions are reported to make up as much as 25 percent of injuries, while ligamentous injuries with strains and sprains combined, accounted for 16 - 47 percent of all injuries. Fractures ranged between 3 and 27 percent of reported injuries, while a combination of contusions, lacerations and haematomas ranged from 3 to 46 percent. Finally, subluxations and dislocations account for 1 - 11 percent of all injuries. However, the causes of last-mentioned injuries can be classified into contact or non-contact injury categories (Fuller *et al*., 2017:51).

Non-contact knee injuries can be seen as occurring when no significant external force is applied directly to the knee joint (Corban, Lorange, Laverdiere, Khoury, Rachevsky, Burman & Martineau, 2021:1). Moreover, non-contact injuries etiology is linked with soft-tissue injuries that result from insufficient recovery time and extreme training loads (Windt & Gabbett, 2017:128). Furthermore, poor neuromuscular control, muscle imbalances and weak core strength, make athletes more susceptible to this type of injury due to the repetitive loads forced upon these dysfunctional movement patterns (Tee, Klingbiel, Collins, Lambert & Coopoo, 2016:3194).

Table 2.1: Injured body site percentage due to contact/non-contact

Body Hemisphere	Body Part	Injury %	Contact / non-contact	References
Upper limb	All	16 – 29%	Both	Brazier, Antrobus, Stebbings, Day, Heffernan, Cross & Williams (2019:138) and Fuller, Taylor, Kemp & Raftery (2017:51)
	Head/concussion	10 – 22%	Both	
Lower Limb	All	48 – 63%	Both	
	Hamstring	6 – 15%	Both	
	Knee	11 – 22%	Both	

Table 2.1 reports that lower body injuries occur more frequently than upper body injuries, be it due to contact or non-contact scenarios in rugby. Of all lower body injuries, the knee joint has the highest incidence rate, which is a major concern to athletes, coaches, and rehabilitation specialists.

Table 2.2: Muscle tendon injury percentage in lower body due to contact/non-contact

Injury type	Injury %	Contact / Non-contact	References
Muscle contusion	9 – 20%	Non - contact	Fuller, Taylor, Kemp & Raftery (2017:51) and Williams, Trewartha, Kemp, Brooks, Fuller, Taylor, Cross & Stokes (2016:651) Montgomery, Blackburn, Withers, Tierney, Moran & Simms (2018:994)
Muscle rupture	26 – 40%	Non - contact	
Tendon Rupture	33 – 48%	Non - contact	
ACL rupture	57%	Contact	
ACL rupture	43%	Non-contact	

Table 2.2 indicates that a tendon rupture injury is most prevalent in the lower limb, during either contact or non-contact related injuries. However, the injuries of concern are those causing the most days absent, In this regard literature indicate that 14 percent of ACL injuries occurred through non-contact mechanisms, including cutting, pivoting, and twisting (Fuller, Taylor, Kemp & Raftery, 2017:55). Video analysis by Montgomery, Blackburn, Withers, Tierney, Moran, and Simms (2018:994) indicated that only 57 percent of ACL injuries occurred during contact, whilst the remaining 43 percent occurred through non-contact mechanisms, being mainly cutting and pivoting (sidestepping) manoeuvres.

When looking at the number of days absent from game play and practice until full return to play, at the same level of competition from the day of injury onset, the knee ligament injuries accounted for 1507 days of absence (29%), making it the most days absent when compared to *hamstring* strain causing 669 days-absence (13%), and shoulder dislocation causing 321 days-absence (6%) (Fuller *et al*., 2017:55). While the occurrence, nature and inciting events related with match injuries at Rugby World Cup

(RWC) 2015 were parallel to those reported previously for RWC 2007 and RWC 2011, there were increasing trends in the mean severity and total days-absence through injuries (Williams *et al*., 2016:651). Research proclaims that there is a need to develop effective prevention strategies for the increased number of knee ligament injuries, hence the reason why the researcher of this study looked at why knee injuries caused the most days absence, rather than being the most common injury (Fuller *et al*., & Williams *et al*., 2016:657).

Knee injuries, particularly ACL and medial collateral ligament (MCL) injuries caused the greatest absence for forwards and backs, with *hamstring* injuries being the third greatest absence (Fuller *et al*., 2017:51). Although ACL injuries are in the top five most severe injuries for six of the last seven rugby seasons, they have not been among the most frequent injuries (Fitzpatrick *et al*., 2018:160). Literature stated that ACL tears were the most severe rugby injury in terms of days absence, although not the most frequent (Hind, Konerth, Entwistle, Theadom, Lewis, King, Chazot & Hume, 2020:11). Although the above-mentioned study calculated severity from date of occurrence until date of return to full training, which differs from the Rugby Union’s consensus statement on injury definitions and data collection procedures, which could lead to an increased severity of data, other literature still agrees with their statement (Fitzpatrick *et al*., 2018:160; Fuller, Molloy, Bagate, Bahr, Brooks, Donson, Kemp, McCroy, McIntosh, Meeuwisse & Quarrie, 2007:328).

Often ACL injuries lead to joint effusion, muscle weakness, altered movement and reduced functional performance (Montalvo, Schneider, Webster, Yut, Galloway, Heidt, Kaeding, Kremcheck, Magnussen, Parikh & Stanfield, 2019:472). ACL injuries have also been associated with continuing clinical trauma such as meniscal tears, chondral lesions, and an increased risk of early-onset post-traumatic osteoarthritis (Khan, Alvand, Prieto-Alhambra, Culliford, Judge, Jackson, Scammel, Arden & Price, 2019:965). Even though concussions have been cited as the most prevalent injury in rugby, it is still lower body ligamentous injuries such as the ACL rupture that keeps players away from game participation for extended periods of time (Mantalvo *et al*., 2019:472).

2.7 ANTERIOR CRUCIATE LIGAMENT INJURIES

Anterior Cruciate Ligament (ALC) re-injury in rugby players post ACLR remains high. Up to 30 percent of active patients who received reconstruction suffered a second ACL rupture within the first two years after the primary reconstruction, with the highest percentage of injury reoccurrence taking place between 6-12 months after reconstruction (Stanley, Harkey, Luc-Harkey, Frank, Pietrosimone, Blackburn & Padua, 2019:21). Literature states that the return to pivoting and cutting sports increases the athlete's chances for an ipsilateral second and contralateral ACL injury by five times, respectively (Arundale, Capin, Zarzycki, Smith & Snyder-Mackler, 2018:422). Secondary ACL tears increase the likelihood of being diagnosed with posttraumatic knee osteoarthritis by 13 – 48 percent (Grindem *et al*., 2016:804). Most of these studies were performed on elite athletes suggesting that there are shortcomings of existing studies that highlight the need for more studies on amateur athletes.

2.7.1 Mechanism of Anterior cruciate ligament injury

Sports related injuries that led to the detection of athletes at risk for lower extremity injuries, as well as the implementation of injury prevention programs, have become common in research (Clark & Clacher, 2020:43; Vaulerin, Chorin, Emile, d'Arripe-Longueville & Colson, 2019:8). Anterior Cruciate Ligament injuries are typically the result of a non-contact injury, whereby a combination of movements such as femoral adduction and internal rotation, knee flexion or tibial rotation with the foot and ankle in a valgus moment, result in partial or complete ACL tears (Wetters, Weber, Wuerz, Schub & Mandelbaum, 2016:6). In agreement with this, Zhang, Hacke, Garret, Liu, and Yu (2019:453) denoted that injury risk was increased when sport participants fixed one foot on the ground with the knee abducted, and the hip flexed while performing movements. The risk of injury explains why an increased lateral tibial plateau slope is an important variable when predicting high-grade rotatory laxity in ACL injuries (Rahnemai-Azar, Abebe, Johnson, Labrum, Fu, Irrgang, Sameulsson & Musahl, 2017:1170).

Rapid deceleration of the lower limb with the *quadriceps* fully contracted and the knee in extension, also creates a high injury risk (Montgomery, Blackburn, Withers, Tierney, Moran & Simms, 2018:994). Literature denotes that most of the non-contact ACL injuries results from cutting or pivoting (sidestepping) manoeuvres where initial ground contact was through heel strike (Montgomery *et al*., 2018:994). Heel strike is significantly associated with non-contact ACL injury (Montgomery *et al*., 2018:994).

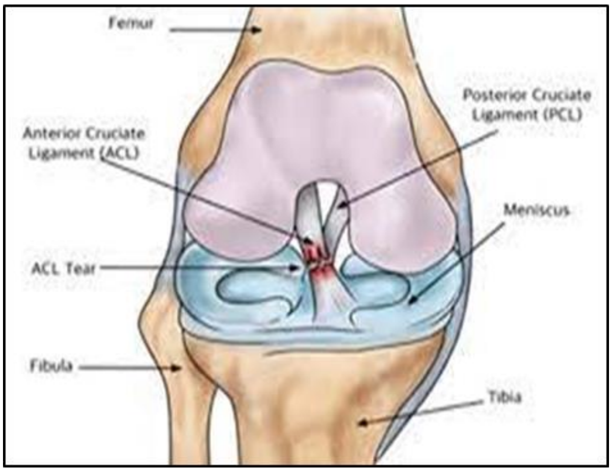

Figure 2.3: Anatomy of a torn ACL (Abulhasan & Grey, 2017:34).

The non-contact mechanism has repeatedly been associated with a failure to maintain knee neuromuscular control (Koga *et al*., 2018:333). Even though Alentorn-Geli, Alvarez-Diaz, Ramon, Marin, Steinbacher, Rius, Seijas, Ares and Cugat (2015:2502) claimed that the neuromuscular characteristics, in terms of contractile and mechanical properties of the gastrocnemius muscles, may not be a significant ACL injury risk factor, after using tensiomyography, research suggests that there is inconclusive evidence to support this statement (Koga *et al*., 2018:335). The anterior tensioning on the proximal tibia, exposing the ACL to an increased tensile load, is caused by muscular forces around the knee, the *quadriceps* and gastrocnemius naturally countered by the *hamstring*s (Wetters *et al*., 2016:22).

2.7.2 Risk factors related to ACL injury

Cutting, singular-legged stance, jump landing and torsional movements are typical predisposing to non-contact ACL injuries (Volpi, Bisciotti, Chamari, Cena, Carimati & Bragazzi, 2016:480). Silvers-Granelli, Bizzini, Arundale, Mandelbaum and Snyder-

Mackler (2017:2447) added that a disturbance of the balance caused by an opponent such as a push or disturbance of the landing phase after a jump, can also contribute to an ACL rupture.

Rugby is a sport played both nationally and internationally with a high incidence of ACL injury. Therefore, understanding risk factors of an ACL tear is crucial. Risk factors related to ACL injuries can be split into intrinsic and extrinsic factors, where intrinsic can be further divided into modifiable and non-modifiable risk factors. For the purpose of this study the researcher only focused on intrinsic factors as the extrinsic variables are housed within the ecological theories. This is not a focus area of physical injury rehabilitation and therefore has been discussed very superficially as part of the current study outcomes.

Some of the common intrinsic non-modifiable risk factors cited in literature consist of family history, leg length discrepancy, structural knee valgus, knee recurvatum, joint laxity, female gender, decreased intercondylar notch width, history of contralateral knee ACL injury, and an increase in the lateral tibial slope (Price, Tuca, Cordasco & Green, 2017:55). Age and the level of activity participated in, plays a vital role in deciding the appropriate treatment for ACL injury, as the function of the ACL during normal daily activities is less important than during high, physically demanding tasks (Wang *et al*., 2011:3551).

Similarly, Wetters *et al*., (2016:2) identified additional neuromuscular and biomechanical risk factors, which may be intrinsic modifiable. Lower limb biomechanics seem to be affected by an increased pelvic tilt and femoral anteversion, causing the relative tensioning of lower limb muscles to be affected (Keays, Newcombe & Keays, 2020:1826). Studies showed that an increased pelvic tilt can ultimately lengthen and weaken *hamstring*s and gluteal musculature, which causes increased anterior tibial translation, while reduced gluteal strength may predispose athletes to a valgus collapse during cutting and pivoting movements (Rajagopal, Dembia, DeMers, Delp, Hicks & Delp, 2016:2068; Wetters *et al*., 2016:3).

Literature suggests that repeated stretch-shortening movements such as cutting, tackling, jumping, and sprinting elicits fatigue in rugby athletes (Wiggins, Grandhi, Schneider, Stanfield, Webster & Myer, 2016:1861). An additional intrinsic modifiable risk, and possibly the most important risk factor, is the effect that neuromuscular fatigue has on the competency of the knee joint, specifically the ACL. Chappell, Herman, Knight, Kirkendall, Garrett and Yu (2005:1022) concluded that after inducing fatigue on the lower legs, fatigued athletes showed altered motor control strategies, indicating that there are large amounts of strain on the ACL, increasing the anterior tibial shear force and overall risk of non-contact ACL injuries. Due to altered neuromuscular control when fatigue is present, these asymmetries could occur recurrently (Lonergan, Senington, Patterson & Price, 2018:238).

2.8 INJURY PROFILING ELITE VS AMATEUR TEAMS

In elite rugby, there appears to be a trend towards more severe injuries. Whether it is due to a more conservative injury management approach, or increased damage caused by bigger collisions, remains unclear (Fuller *et al*., 2017:51).

Match injury data was captured during the 2019 Currie Cup Premier Division Competition. The total time-loss injury rate of 74 – 113 injuries per 1000 player hours, was higher than the international time-loss injury rate of 63 – 105 injuries per 1000 player hours (Starling *et al*., 2020). The Toyota Free State Cheetahs obtained the highest injury rate for time-loss injuries, but the team’s injury rate was not significantly higher than the tournament average (Starling, 2019:2). Contrary to this, the Toyota Free State Cheetahs went on to win the 2019 Currie Cup Premier Division. The Currie Cup 2019 led to 28 – 53 muscle/tendon injuries per 1000 match hours, followed by 12 – 30 ligament injuries per 1000 match hours (Sewry, Verhagen, Lambert, Van Mechelen, Marsh, Readhead, Viljoen & Brown, 2018:2066). The head was the site associated with the most injuries (11 – 29 head injuries per 1000 match hours) followed by the knee (5 – 18 knee injuries per 1000 match hours) (Starling *et al*., 2020). The MCL injury was the most frequent knee injury, and these results link well with the international research of West (2018:60) stating that the MCL was in the topmost frequent knee injuries.

2.9 MANAGEMENT OF ACL RUPTURES

Anterior cruciate ligament injuries can be treated in two main ways, namely, conservative, and non-invasive or surgical reconstruction. Non-operative approaches may be considered in lower, physically demanding patients, but may result in constant instability, and are not cost-effective for athletes (Saltzman, Cvetanovich, Nwachukwu, Mall, Bush-Joseph & Bach, 2016:1329).

A conservative approach after ACL injury can broadly follow five goal orientated phases of rehabilitation (Huang, Salmon & Heath (2017:112). Phase 1 - Acute Recovery. During this phase, the focus is to minimise any form of swelling around the knee joint and to restore the full knee range of motion. Phase 2 - Muscular Control and Coordination. Closed kinetic chain body weight related movements are the focus, where open kinetic chain movements are avoided, as it can apply strain to the vulnerable ACL (Gokeler, Neuhaus, Benjaminse, Grooms & Baumeister, 2019:857). Phase 3 - Proprioception and Agility. While the need to continue with strength training is still prevalent, the emphasis shifts more to balance, agility and proprioception improvement. Neuromuscular training has been shown to be superior to strength training alone and should coherently be addressed during this phase (Van Melick, Van Cingel, Brooijmans, Neeter, Van Tienen, Hullegie & Nijhuis-van der Sanden (2016:1510). Phase 4 - Sport Specific Skills. Simplified sport specific drills must commence in this phase. It is very important to continue with strength exercises with a focus shift to the speed of force production (Grindem *et al*., (2016:807). Phase 5 - Return to Play. A gradual increase in time of sport should be implemented, starting with no longer than 20 minutes of return to sport (Kyritsis, Bahr, Landreau, Miladi & Witvrouw (2016:949).

Electromyograph (EMG) signal amplitude shows both linear and non-linear relationships with the force produced by the muscle (Enoka, 2019:71). Khaiyat and Norris (2018:644) provided evidence for optimal prescription of training and rehabilitation exercises in athletes with ACL injury, by means of strengthening and muscle activation, explaining why EMG has been used as a conservative treatment modality to support potential rehabilitation exercises through biofeedback seeing how much muscle activation is produced and potentially augment stability, strength, and endurance in the involved limb. Tomescu, Bakker, Wasserstein, Kalra, Nicholls, Whyne and Chandrashekar (2018:528) concluded that the use of a brace with a dynamic tensioning system is sufficient to lower strain on the menisci in ACL deficient knees. Kalra, Bakker, Tomescu, Polak, Nicholls and Chandrashekar (2019:132) support this notion that bracing may be beneficial in further ACL injury prevention or, in protecting the ACL graft in the wake of a reconstruction. From bracing helping the external stabilisers it is important to focus on the internal physiological management techniques such as platelet rich plasma (PRP) injection as well.

A PRP injection is known to be comprised of blood platelets and a few growth factors involving platelet derived growth factor and transforming growth factor-beta (You, Chou, Wu & Hsu, 2019:148). Both these factors are regarded to be the most critical modulators in the healing procedure as they facilitate collagen production and enhance proliferation (You, Chou, Wu & Hsu, 2019:149). During embryologic tendon development, transforming growth factor-beta is a key regulator, and plays a vital role in the early modulation of scar tissue during recovery (Murray, Rice, Wright & Spector, 2003:238). After five years post an ACL tear, patients treated with ACL reconstruction versus rehabilitation alone did not differ in *quadriceps* strength, single-legged hop test performance, activity level, pain, symptoms and activities of daily living, or presence of knee osteoarthritis (Shukla *et al*., 2019:58; Wellsandt *et al*., 2018:2103).

The use of femoral nerve block at the time of primary ACL reconstruction can negatively affect achievement of isokinetic extension strength and return to sport criteria (Christensen, Taylor, Hetzel, Shepler & Scerpella, 2017:232). Femoral nerve blockade increases the risk of a graft rupture within the first year after surgery but does not affect re-injury risk during the second year (Kline, Morgan, Johnson, Ireland & Noehren, 2015:2553). Limited number of authors have investigated the effects of alternative intense exercises, such as anaerobic lactic acid exercises, that may also impair proprioceptive skills (Romero-Franco, Martinez-Lopez, Hita-Contreras, Lomas-Vega & Martinez-Amat, 2014:205). There seems to be no evidence-based argument to recommend surgical reconstruction alone as an optimal option for any patient who tore their ACL (Shukla *et al*., 2019:58).

On the contrary, Mistry, Metcalfe, Colquitt, Loveman, Smith, Royle and Waugh (2019:1782) believe that even though ACL ruptures can be managed conservatively, reconstruction results are considered better when looking at knee stability. ACL reconstruction has two main types of grafts to be used. Mainly auto graft, coming from a specific site from the patient's own body, and an allograft coming from another person's body. Artificial grafts tend to come more into play when the patient is going for a second reconstruction of the same ACL (Jia, Xue, Wang, Liu, Huang & Xu, 2017:11).

Autografts can be derived from different source tendons. The most common source, according to recent studies, seems to be *hamstring* tendons, but some surgeons prefer bone-patellar-tendon-bone (BPTB) as first line, and others use BPTB in clients who are high risk (Hulet, Sonnery-Cottet, Stevenson, Samuelsson, Laver, Zdanowics, Stufkens, Curado, Verdonk & Spalding, 2019:1754). Allografts come from various sites, including tibialis anterior, *quadriceps*, achilles tendon, BPTB and *hamstrings* (Mistry *et al*., 2019:1782).

Literature advocates that BPTB autograft is the most favourable graft choice due to faster graft incorporation, with a larger proportion of patients returning to pre-injury activity levels, and probable lower risk of graft rupture (Samuelsen, Webster, Johnson, Hewett & Krych, 2017:2459, Xie, Liu, Chen, Yu, Peng & Li, 2015:100). However, others favour the four-strand *hamstring* autografts, because of lower donor site morbidity, anterior knee pain, osteoarthritis, and extensor strength deficit (Thompson, Salmon, Waller, Linklater, Roe & Pinczewski, 2016:3083, Sugimoto, Myer, McKeon & Hewett, 2012:979). Although debate remains on detailed advantages and disadvantages, graft rupture and subsequent revision surgery is evidently the most noteworthy adverse outcome after ACL reconstruction. The use of a *quadriceps* tendon graft has led to equal or better functional results compared to the *hamstring* graft, without distressing morbidity (Cavaignac, Coulin, Tscholl, NikMohd Fatmy, Duthon & Menetrey, 2017:1326).

The advantages of allografts include no donor site morbidity, a shorter operation and less painful initial recovery (Wasserstein, Sheth, Cabrera & Spindler, 2015:207). The disadvantages are slower graft incorporation and concern about higher rupture rates in some younger, highly active groups, concerns about disease transmission and increased cost (Yoo, Song, Shin, Kim & Seon, 2017:1290). The concern about a higher re-rupture rate may not be warranted and may date from the time when allografts were weakened when irradiated or chemically cleaned (Zeng, Gao, Li, Yang, Luo, Li & Lei, 2016:153). There are no significant variances in clinical efficacy between autografts and non-irradiated allografts (Hardy, Casabianca, Andrieu, Baverel & Noailles, 2017:245). Literature is still inconclusive as to whether elite sprinting athletes may be influenced by the effect of autograft harvesting on the athletes' specific sport, or not (Samuelsen *et al*., 2017:2459). The type of graft should be considered with the different risk factors associated with ACL injuries to limit the re-injury after ACL reconstruction.

Literature shows a decreased prevalence of criterion-based rehabilitation approaches for returning to sport after ACL reconstruction, combined with psychological readiness (Joreitz, Lynch, Harner, Fu & Irrgang, 2017:397). Di Stasi, Myer, and Hewett (2013:778) claim that electrical muscle stimulation (EMS) of the *quadriceps* and *hamstring*s can have a positive effect in isometric muscle strength gains, which could ultimately lay the foundation towards knee proprioception recovery. There is a wide variety of conservative and invasive ACLR management techniques. It is not clear as to which management techniques works significantly better than the other. A deeper look into the relationship between the intrinsic factors (age, gender, ethnicity) and the treatment plan used in conjunction with the ACL re-injury rate should be further investigated.

2.10 KNEE JOINT PROPRIOCEPTION

The definition of proprioception, as reported by Sherrington (1906:101), is "the perception of joint and body movement, as well as position of the body, or body segments in space" and, the "perceptions of the relative flexions and extensions of our limbs". Sherrington (1906:101) refers here to proprioception as body movement perception and position, which is the identification, interpretation and organisation of sensory information needed for humans to internally represent and comprehend their environment (Han *et al*., 2016:80). The foundation for the advancement of task-specific neural development is reasoned to be proprioception (Xerri, 2012:133; Han *et al*., 2016:80).

However, for the purpose of this study, the researcher will contextualise the definition for proprioception as being the ability to sense stimuli arising within the body regarding position, motion, and equilibrium (Han *et al*., 2016:81). This definition suits the study better, as it explains the variables the researcher focused on, namely, body position correction during motion, or dynamic stability. Proprioceptors are located in the joint capsules, muscles and surrounding tissues signalling information to the central nervous system about position and movement of body parts (Tuthill & Azim, 2018:194). Proprioception plays the most important role in joint function by which the body can vary muscle activation in immediate response to incoming information regarding external forces (Sharma, 2017:13). The development of sport motions is predominantly led by proprioception and may maximise performance and prevent injuries in athletes as it informs the body's position from muscles, tendons, joints, as well as skin (Romero-Franco *et al*., 2014:205).

Numerous studies concluded that integral joint position was a prerequisite for typical muscle co-ordination and correct feedback to the central nervous system (Han *et al*., 2016:80). Researchers also argue that muscular fatigue led to proprioceptive deficits in joints (Romero-Franco *et al*., 2014:205; Matthews, Green, Matthews & Swanwick, 2017:118). The ability to sense joint position, the human proprioceptive system can similarly sense movement and perceive weight and force from both central and peripheral indicators (Sharma, 2017:13). Some researchers consider kinematic aspects such as the sense of effort, heaviness, and effort to be components of proprioception (Sarabon, Panjan Rosker & Fonda, 2013:431; Proske & Gandevia, 2012:1651). However, it is still indistinct whether there are definite relationships between force related and movement related aspects of proprioception, or not.

Proprioception requires the stimulation of mechanoreceptors to commence by means of body movements, which could be enhanced by memory and learning, and does not exclusively rely on the passive receipt of sensory signals (Vafadar, Cote & Archambault, 2016), indicating that proprioception has both psychological and physiological characteristics. The central and peripheral mechanisms underlying proprioceptive control are still varied, meaning that in sport and physical activity, there is no consensus on proprioceptive improvement linked with exercise because of peripheral adaptation, neural plasticity, or both (Raymond & Hiller, 2019; Nodehi-Moghadam, Nasrin, Kharazmi & Eskandari, 2013:4). Furthermore, whether the superior proprioceptive ability in some athletes is due to rigorous training or is determined by genetic factors remains unidentified (Han *et al*., 2014:159; Sarmento, Anguera, Pereira & Araujo, 2018:907). Despite the varied mechanisms, the significance of proprioception has been well recognised in sport performance selection, sports injury prevention and rehabilitation, talent identification and fall risk prediction in the elderly (Sell & Lephart, 2018:133; Han *et al*., 2016:80).

i. An injury such as a torn ACL, damages the soft tissue where these proprioceptors are located, ultimately causing abnormal functioning, resulting in a loss of proprioception (Arockiaraj *et al*., 2013:189; Kaya, Callaghan, Yosmaoglu & Doral, 2018:123). This correlates well with the ligament dominant theory, but also helps create possible evidence for the quad dominant and leg dominant theories of ACL injury risk factors (Alentorn-Geli *et al*., 2009:705). The ligament dominance theory suggests that athletes with high ACL injury risk perform cutting, pivoting and landing manoeuvres with extreme dynamic knee valgus, hip adduction and hip internal rotation (Pappas, Nightingale, Simic, Ford, Hewet & Myer, 2015:677). The *quadriceps* dominance theory, which propose that the quadriceps stabilises the knee joint by primarily using the *quadriceps* muscles, which pulls the tibia anteriorly to the femur causing shear stress in the ACL. The leg dominance theory, which indicates that during athletic responsibilities leg dominance, non-requiring leg dominance and force asymmetry could potentially predispose the ACL to injury.

Currently, literature suggests that there are four methods to test proprioception, namely:

i. Threshold to detect passive motion (TTDPM) - The TTDPM proprioception technique can be categorised under the method of limits category, where participants are required to detect joint movement under different velocities (Sahin, Dilek, Baydar, Gundogdu, Ergin, Manisali, Akalin & Gulbahar, 2017:857).

ii. Joint position reproduction (JPR) - The JPR proprioception test protocol is a form of the method of adjustment, where participants are asked to replicate or match the formerly experienced reference joint positions using their contralateral or ipsilateral limb (Ouattas, Wellsandt, Hunt Boese & Knarr, 2019:197).

iii. Active movement extent discrimination (AMEDA) - In contrast to the two techniques previously mentioned, the AMEDA test uses the absolute judgement method, where the matching number of stimuli and responses are used (Mi, Katkov & Tsodyks, 2017:323). This technique was developed and validated for testing proprioception at the knee, hip, lumbar spine, cervical spine, shoulder, and hand (Han *et al*., 2016:80; Ghai, Driller & Ghai, 2017:65)

iv. The star excursion balance test (SEBT) is a common screening tool for dynamic stability of the lower extremity in the athletic population (Stiffler, Bell, Sanfilippo, Hetzel, Picket & Heidersciet, 2017:339). The SEBT consists of a series of eight unilateral balance tests that integrate a single-leg stance of one leg, with a maximum targeted reach of the free leg. The stance leg functions in the closed kinetic chain, with joined motion at the hip, knee, and ankle joints, as the opposing leg reaches in the specified direction. As the targeted reach is achieved with the foot, the postural control system is challenged as the body's centre of mass is shifted in relation to its base of support. Postural control is facilitated by the vestibular, somatosensory, and visual systems. Adequate neuromuscular control and proprioception of the muscles of the stance leg is vital to increasing the length of excursion of the reach leg. Thus, optimal performance of these tests can only be achieved if there are no restrictions to range of motion or neuromuscular control at the involved joints (McCan, Crossett, Terada, Kosik, Bolding & Gribble, 2017:992; Stiffler *et al*., 2017:339).

The SEBT has presented good validity (excellent concurrent validity) and even better reliability (ICC = 0.84 – 0.92) (Munro & Herrington, 2010:130; Bastien, Moffet, Bouyer, Perron, Hebert & Leblond, 2014:47). It must be considered that there is a significant learning effect with repetitive trials of four to eight excursion directions (Gibson, Wagner & Heyward, 2018). Hence, no familiarisation excursions are given by researchers to limit the learning effect. The SEBT scores are divided by the participant's functional leg length then multiplied by 100, to normalise data and compare it against the rest of the participants. Research shows that having good dynamic stability reduces the risk of injury, and it increases sport performance (Kwon

& Williams, 2017: 143; Zulfikri & Justine, 2017:16). However, these advantages may be limited after fatigue.

2.11 NEUROMUSCULAR FATIGUE

Neuromuscular fatigue encompasses a decrease in neurological function when muscle performance capacity decreases as a result of fatigue (Sharma, 2017:13). Muscle fatigue is defined as a transient decrease in maximal voluntary performance capacity of a muscle (Montgomery *et al*., 2018:995). This, in essence, means that researchers can expect to see metabolic changes that are associated with a fatigued state. The metabolic changes that accompany fatigue directly affect the contractile pathways and activate afferents which may induce a reduction in force. Metabolic changes may include, for example: depletion of ATP levels and neurotransmitter reserves, increased concentration of inorganic phosphates at the cross-bridge level, increased hydrogen ion concentration, decreased intracellular potassium ion concentration, an increase in extra cellular potassium ion and increased threshold of synaptic or motor end plate receptors, which all lead to the decline in muscle performance capacity (Sharma, 2017:13; Matvienko, Zavodovskyi, Nozdrenko, Mishchenko, Motuziuk, Bogutska & Prylutskyy, 2017; Staiano, Bosio, de Morree, Rampinini & Marcora, 2018:175). This explanation indicates that no matter the activity of the lower limb, there should always be a decrease in performance after a certain amount of fatigue.

However, the correlation between impaired function during fatigue and reduced pH is not always present, as force sometimes recovers more rapidly than pH after the end of fatiguing activations (Rashedi & Nussbaum, 2017:26). It can therefore be deduced from the literature, that if reduced pH has a direct force-depressing effect on human muscles, this effect must be countered by another factor that increases force to a similar degree (Zulfikri & Justine, 2017:16). It has been proposed that the afferent feedback system may be interrupted, as fatigue seems to affect active joint reposition sense, ultimately resulting in less accurate information from the muscle spindle (Joudeh, Alghadir, Zafar, Elwatidy, Tse & Anwer, 2018:248). This correlates well with the fact that most contact and non-contact lower limb injuries occur in the last 20 minutes of a rugby game and could therefore possibly be ascribed to neuromuscular fatigue ans subsequent susceptibility of the lower limb injury (Montgomery *et al*., 2018:995).

The neuromuscular system is highly adaptable and quickly responds to new patterns of muscular activity. In the earliest phase of muscular training, changes in the production of force may be due to neuromuscular adaptations related to learning optimal muscle activation patterns (Mettler & Griffin, 2016:267). Increases in motor unit firing rate, and earlier motor unit recruitment, occur during the first few weeks of resistance training, and the motor unit firing rates, during brief non-fatiguing activations, were higher after resistance training (Contessa, De Luca & Kline, 2016:1579; Martinez-Valdes, Falla, Negro, Mayer & Farina, 2017:1126). Additionally, the athlete's precision of the knee joint position sense also deteriorates after anaerobic lactic exercise. This loss is recovered within 30 minutes (Romero-Franco *et al*., 2014:205).

Several studies have shown that muscular fatigue produces an excessive deal of proprioceptive deficits concerning movement sense and postural control, along with passive repositioning of the joints (Yang & Ma, 2018:1145; Flevas, Bernard, Ristanis, Moraiti, Georgoulis & Pappas, 2017:1903). Montgomery *et al*., (2018:995) found that 47 percent of all non-contact ACL injuries occurred in the last 20 minutes of a rugby match. The above-mentioned authors also stated that 89 percent of heel strike ACL injury cases occurred in the second half of the match, and went further to hypothesise that irrespective of injury, fatigue plays an important role in determining the nature of the foot strike, which automatically predisposes rugby players to ACL injuries.

Despite the evidence about proprioceptive impairment after intense exercise, the duration of this depletion is still unclear (Romero-Franco *et al*., 2014:205). Barber-Westin and Noyes (2017:3391) concluded that current published fatigue protocols did not consistently generate variations in lower limb neuromuscular factors that amplifies the risk of non-contact ACL injuries. Therefore, justification does not currently exist for major changes in ACL injury prevention training programs to account for potential fatigue effects.

Anterior cruciate ligament reconstructed patients have altered neural responses, capable of impacting motor function, and specifically, a diminished ability to generate descending action potentials and motor output, ultimately leading to weaker neuromuscular control (Lepley, Grooms, Burland, Davi, Kinsella-Shaw & Lepley, 2019:1267). However, neuromuscular training, enhancing unconscious motor responses by stimulating both central mechanisms and afferent signals, which are responsible for dynamic knee joint stability, needs more research (Van Melick *et al*., 2016:1506). Dysfunctional *quadricep* activation patterns can generate irregular motor activation patterns, which could lead to a higher risk of re-injury (Charles, White, Reyes & Palmer, 2020:882).

2.12 SURFACE ELECTROMYOGRAPHY

Recording biological signals offers a primary gateway to the awareness of how the human body performs under normal and clinical conditions. Disability, pain, and loss of life quality have been caused by an impairment of muscular activation (Lepley, Grooms, Burland, Davi, Kinsella-Shaw & Lepley, 2019:1269). The preservation and restoration of movement performance has always been a challenge in a clinical setting (Disselhorst-Klug, Williams & Von Werder, 2018:1014). Consequently, technologies that enable more effective treatment and screening benefits have gained popularity with the evidence-based standing increasing steadily (Garcia & Vieira, 2011:20). Information, concerning muscle activation for instance, myoelectric manifestation of muscular fatigue, muscle activation intensity and the recruitment of motor units, are often conveyed by surface electromyography (Kosuge, Itakura & Mito, 2013:225).

Electromyography (EMG) is where electrodes are placed on the skin surface over a specific muscle belly to pick up the level of muscle activation in microvolts. EMG is a non-invasive tool that allows for a pain free, objective, neuromuscular activation assessment during dynamic tasks (Bu, Guo, Ma, Xu & Wei, 2018:552). For this study, the definition of EMG, as proposed by Phinyomark, Campbell and Scheme (2020:16), namely, the process where electrical activity produced by the muscle, throughout the body, is measured using skin surface or intramuscular electrodes, will be used.

Intentional and reactive motor pathways behaviour have only recently started to be fully understood through using EMG. The identification and analysis of the electrical potential produced during muscle activations is the primary focus of this technique (Garcia & Vieira, 2011:20). EMG’s can be detected in two keyways, either indirectly, with surface electrodes placed on specific skin sites directly above the muscular tissue, or by directly inserting electrodes into the muscular tissue (Kwon, Rutkove & Sanchez, 2017:1748). Surface electrodes are more popular in the rehabilitative and sport science community due to their non-invasiveness (Luo, Liu & Yang, 2019:64859). Neuromuscular compartment identification can correspondingly be recorded using high-density surface EMG.

The study of muscle activity during dynamic lower limb tasks is important in a clinical setting (Agostini, Ghislieri, Rosati, Balestra & Knaflits, 2020:5). The sort of muscle activity monitoring is related to the management of various neurological patients (Parkinson disease, post-stroke, multiple sclerosis and hemiplegic adults and children after cerebral palsy) and orthopaedic conditions such as post ACL reconstruction, total knee arthroplasty and total hip arthroplasty (Frigo & Crenna, 2009:237, Campanini, Disselhorst-Klug, Rymer & Merletti, 2020:934). Therefore, muscle activity during dynamic lower limb stabilisation will be applicable in this study, as the researcher wants to establish whether there is a difference in *quadriceps* activation between the involved and uninvolved lower limbs, as well as between a fatigued and non-fatigued state, or not.

A key component of EMG technology is comparing the involved to the un-involved side, as Flaxman, Alkaer, Smale, Simonsen, Krogsgaard and Benoit (2019:115) reported muscle activation pattern differences. Since the neuromuscular system integrates activity of all muscles crossing the knee to create a moment-of-force that defies an external load, Benazzouz and Slimane (2021:17) recommend the use of individual muscle EMG to identify any irregularities between the involved and un-involved lower limb knee muscle activation. Current and empirical research seems to be focused on static knee strength and stability post ACLR. A gap in research has been identified, as there is an absence of studies that focus on knee muscle activation during dynamic stability tests, post ACLR, to assess the possibility of re-injury (Smale, Alkajer, Flaxman, Krogsgaard, Simonsen & Benoit, 2019:581).

EMG has the potential to tell the clinician how to modify physical rehabilitation to get an increased amount of muscle activation. When looking at un-injured lower limbs during a fatigue protocol, it has been noted that fatigue during the sit-to-stand exercise increases the percentage of maximum voluntary activation of the quadricep muscles with every further repetition (Roldan Jimenez, Bennet, Ortiz Garcia & Cuesta Vargars, 2019:4202). According to Roldan, *et al*. (2019:4202) the fatiguing of firing group III and IV muscle afferents can limit the voluntary activation in upper limbs, indicating that fatigue in the upper limbs could lead to a decrease in upper limb performance. However, Laginestra, Amann, Kirmizi, Giuriato, Barbi, Ruzzante and Venturelli (2021:2) concluded that any form of 'crossover' of central fatigue in the lower limbs is not facilitated by group III and IV muscle afferents. This, after studying the properties of group III and IV muscle afferent firing between the non-fatigued antagonist and fatigued muscles. This, then begs the question, whether neuromuscular fatigue of the same lower limb could possibly increase percentage of max voluntary activation and ultimately increase dynamic stability performance, or not. Similarly, Carmo Aprigio, De Jesus, Porto, Lemos and De sa Ferreira (2020:102588) proposed that the fatigue of un-injured lower limbs does increase posture instability but is not linked to any variations in movement strategies for up right balance control.

Benazzouz and Slimane (2021:15) suggest that a chief clinical indicator for muscular disorders is muscle activation interval. The findings of the study of Benazzouz and Slimane (2021:15) indicate a weak linear correlation between knee flexion and EMG activation when it comes to atypical cases when assessing gait. Khaiyat and Norris (2018:645) found that a forward lunge rehabilitative exercise, similar to a multi directional lunge during the SEBT, produced significantly higher muscle activation in the *vastus medialis obliques* and *rectus femoris quadricep* muscles. This is of essence in a rehabilitation state, as the *quadricep* muscles atrophy up to 33 percent post ACLR (Charles, White, Reyes & Palmer, 2020:882).

EMG has been used as a form of rehabilitation by using a biofeedback mechanism for a patient to focus more on specific muscle activation. For the best possible prescription of rehabilitation training exercises in ACL injured athletes, EMG signal amplitude has been shown to have both non-linear and linear relations with the amount of muscular force produced (Akima, Tomita & Ando, 2019:102356). It has been broadly used to emphasise potential rehabilitation exercises to enhance strength, stability, and endurance. It is commonly accepted that muscle activation ought to reach 40 percent of its maximum voluntary activation (MVC) threshold throughout rehabilitative exercises to achieve a strength adaptation (Krause & Hollman, 2020:755).

2.13 CHAPTER SUMMARY

This chapter began by providing an overview of the knee joint demands placed on amateur rugby players, and the need for well-developed knee proprioception to be able to successfully execute cutting and pivoting movements. An outline of the key anatomical and physiological parameters that are related to ACL injuries, followed by a descriptive review of rugby related injuries was provided. To adequately place ACL injury contextually, the mechanism of injury is discussed. Finally, this chapter concludes with an exploration of both proprioception and neuromuscular fatigue on ACL injuries and rehabilitation.

Chapter 3 will describe the specific research design, and how the participants were chosen followed by the inclusion and exclusion criteria that had to be met by the participants to form part of the study. Data collection and analysis will also be discussed, as well as the ethical considerations that had to be adhered to.

CHAPTER 3

RESEARCH METHODS AND PROCEDURES

3.1 INTRODUCTION

To achieve the aim of this study, it was important to apply the appropriate research methods and procedures. This chapter outlines the relevant methods and procedures used to carry out the investigation and facilitate repeatability of the study. This chapter begins by describing the research design and appropriate methodology that was chosen to conduct the study, followed by a detailed description of the measuring instruments and the data collecting procedure. Lastly, details relating to the analysis of data and ethical considerations, complete this chapter.

3.2 RESEARCH DESIGN

A quantitative, descriptive, cross-sectional research design was used to explore and describe knee joint competence post ACLR in amateur SWD rugby players. Therefore, only one group of SWD amateur rugby players with ACL reconstruction were tested on two occasions. Both occasions included SEBT testing on the involved and un-involved sides, pre- and post-neuromuscular fatigue protocol, and EMG readings on the involved and un-involved VMO and VL *quadriceps* muscle, pre- and post-neuromuscular fatigue protocol.

3.3 PARTICIPANTS AND SAMPLING TECHNIQUE

Given the descriptive design of the study, non-probability sampling was utilised; specifically, convenience purposive sampling as this method allowed the researcher to select participants based on availability (Suen, Huang & Lee, 2014:105). Amateur SWD club rugby players with ACLR in the last three years (n=15) were recruited for this study. According to Moatshe and Engebretsen (2020:56), ACL injuries are most common between the ages of 16 years - 39 years, therefore participants in this study included amateur male rugby players between 19 and 32 years. Prospective participants, younger than 19 years of age were excluded, as first line consent could not be obtained.

3.4 INCLUSION CRITERIA

To be included in this study the prospective participant must have been:

- a SWD club male amateur rugby player affiliated with SARU,
- an amateur SWD rugby player who turned 19 years (in 2020) and not older than 32 years old,
- involved in any form of moderate intensity exercise four days per week (due to COVID-19 rugby specific training that was suspended in South Africa, which created a two-year period of non-fatigued lower leg muscles, hence the players had to be fatigued to a certain extent to provide an equal starting platform for all participants), and
- be within 3 years post ACLR with clearance from a rehabilitation specialist to return to play.

3.5 EXCLUSION CRITERIA

Participants were excluded from the study if:

- medical clearance from a team physician was not obtained, and
- post screening a potential to injure the knee further due to testing or training had been identified.

3.6 SAMPLE SIZE

The sample size (n=15) was calculated using both a statistical sample size calculator (power analysis). Statistically, the sample size was determined using power analysis performed using statistical software Microsoft Excel® (SAS® 9.4. Cary, NC: SAS Institute Inc.StataCorp. 2021) and Stata Statistical Software: Release 17 (College Station, TX: StataCorp LLC). Furthermore, the sample size of n = 15 correlates with literature in the same field investigating similar inclusion criteria (Arundale *et al*., 2018:422; Lonergan *et al*., 2018:241).

3.7 STUDY SITE

The testing took place at the Potgieter and Pike Biokinetics practice in George, located in the Western Cape Province of South Africa. This practice adhered to all the COVID-19 guidelines as stipulated by legislature during the conduction of this study.

3.8 DATA COLLECTION

Data was collected at Potgieter, and Pike Biokinetics practice located in George. Data collection was carried out by the principal researcher and one assistant Biokineticist. The assistant Biokineticist was fully trained and qualified in conducting tests on the Neuro Trac EMG machine and SEBT scoring. Participants were also advised to not smoke cigarettes or take any form of caffeine (coffee, tea, cola, or energy drinks) one hour prior to testing. Prior to testing the participants were encouraged to perform a warmup as outlined in appendix A. Data was collected between February and May 2021[1]. Results were documented on the relative assessment forms (Appendix C). Data capturing procedures were adhered to according to the national lockdown guidelines by the South African government for the COVID-19 pandemic.

3.8.1 Star Excursion Balance Test (SEBT)

The SEBT is a dynamic stability task that requires neuromuscular control of the stance leg to maintain balance, and to optimise reach distance with the opposite limb in a series of 8 inter-related unilateral balance tests (Gibson *et al*., 2018).

The participant was instructed to stand in the centre of the star which was marked out on the floor. When using the right leg as the reaching leg the participant completed the circuit in a clockwise fashion, indicating that the participants moved anterior, anteromedial, medial, posteromedial, posterior, posterolateral, lateral, and anterolateral culminating at anterior. Conversely, when balancing on the right lower limb, the participant performed the circuit in an anti-clockwise fashion (Fig.3.1).

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[1] Data collection was delayed due to COVID-19 pandemic. Ethical clearance was obtained in September 2020 but due to a title change the updated ethical clearance certificate (appendix B) is dated 27 March 2021

Additionally, participants did not receive any instructions on the balancing technique to avoid any coaching effects. Lastly, the balance-effect of the arms were minimised by asking the participants to always keep their hands on their hips (Rodacki, Fowler & Bennett; 2002:110).

Trials were repeated when a trial was judged to be "non-acceptable" by the researcher and included instances where participants lost their balance, put the reaching foot down in the circuit before completing the circuit, or put too much force on the tape with the reaching foot. These criteria for trial judgements are supported by literature (Talarico *et al*., 2017:1118; Doherty, Bleakley, Hertel, Caulfield, Ryan, & Delahunt, 2015:651).

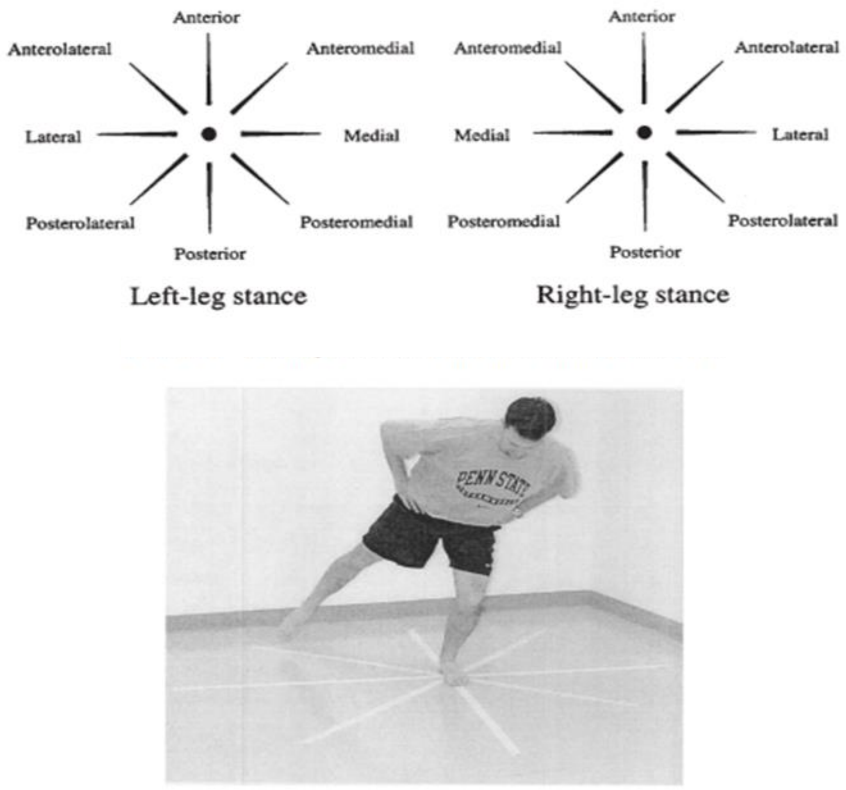


Figure 3.1: Directions of a SEBT Adapted from Gribble and Hertel (2003:89)

Reliability of the SEBT was established in numerous publications noting reliability in healthy participant samples, as well as patients with lower limb injuries such as ACL rupture, and chronic ankle instability (Doherty *et al*., 2015:651, Goto, Aminaka & Gribble, 2018:505). These reliability and validity scores were measured against the gold standard test of the 3D motion capture system named Optotrak 3020 which exhibits high validity, excellent reliability (ICC>.9) during human gait (Bastien, Bouyer, Perron, Hebert & Leblond, 2014:48). Additionally, Gribble, Hertel and Plisky (2012:339) noted that the SEBT should be considered a substantial representative, non-instrumented dynamic balance test. Therefore, the SEBT was deemed by systematic literature reviews to be a reliable test and is valid as a dynamic stability test to predict the risk of lower limb injury, and to identify dynamic balance deficits in patients with a variety of lower limb conditions (Gribble *et al*., 2012:345, Kivlan & Martin, 2012:402). To normalise SEBT scores between individuals, the SEBT score was divided by the participant's anatomical leg length and multiplied by 100 to create a percentage. This exercise allowed the values to be compared between participants.

3.8.2 Electromyography (EMG) biofeedback

Surface EMG biofeedback uses electrodes placed on the participants VL and VMO muscles to convert the myoelectrical signals in the muscle into visual or auditory signals (Giggins, Persson & Caulfield, 2013:60). Verbal permission was obtained by the researcher as to whether he could shave the hair and if the area could be cleaned with an alcohol swab, at the site where the electrodes were to be placed. Anatomical landmarks on the superficial muscles crossing the knee joint, namely the *Quadriceps* (VMO, VL), were palpated to the midpoint of the belly of the specific muscle, as seen in figure 3.2 and only tested during the SEBT.

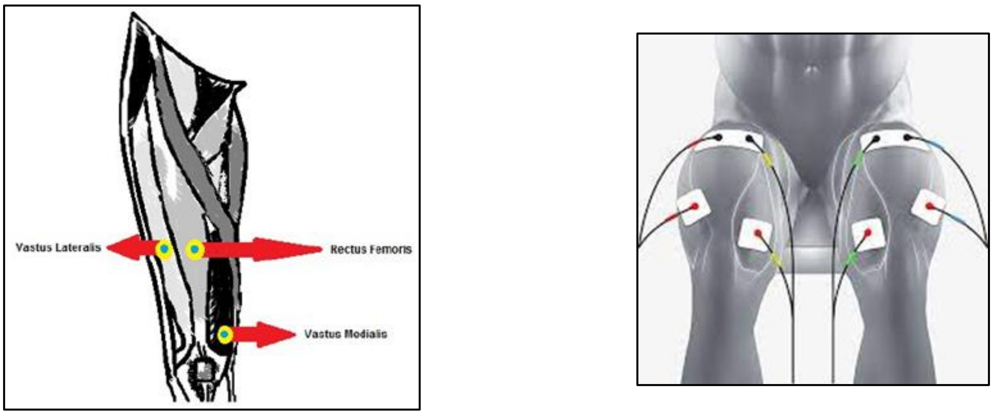


Figure 3.2: Quadriceps electrode placement. Adapted from Segal *et al*., (2017:169)

Once the electrodes were in the correct anatomical location and the connection was secure the participant was instructed to perform a max voluntary activation of the VL and VMO. Thereafter, the electrodes remained on the participant during the pre-fatigue SEBT, switched off during the fatigue protocol and switched back on during the post-fatigue SEBT test in order to record the VMO and VL muscle activation during the SEBT. These results were then used to determine any muscle activation differences between the injured and uninjured limb. Congruently these results could then be compared to any SEBT score deviations. Lynn, Watkins, Wong, Balfany and Feeney (2018:205) noted that surface EMG biofeedback embedded into athletic garments had similar validity and reliability when compared to a research grade system. The researcher used the Neuro Trac Myoplus 4 research grade system due to availability and financial implications, whilst not affecting the reliability or validity of the EMG biofeedback. Smith (2019:116) indicated that the validity and reliability of the Neuro Trac suggest that this apparatus has the potential to be used in dynamic rehabilitation and sport settings.

3.8.3 Neuromuscular fatigue protocol

The fatigue protocol consisted of sets of eight single-leg jumps to at least 90^o of knee flexion, followed by eight Bulgarian split squats with hands on their hips, while ensuring that squatting motions adhered to a steady pace set at 97 Hz by a metronome. This process was repeated until the participant was unable to reach 90^o during the squat or failed to keep pace with the metronome for five consecutive squats. This fatigue protocol was the researcher’s own fatigue design as the researcher is a Biokineticist who works with rugby player rehabilitation as this is the common fatigue protocol used in practice that represents the most consistent fatigue over all individuals. Upon completion of three successful SEBTs in a pre-fatigued state, the participants followed the fatigue protocol to ensure neuromuscular fatigue had been reached. Once the participant failed to maintain knee flexion or the pace set by the metronome, the point of neuromuscular fatigue had been reached. Thereafter the post fatigue SEBT test was done (see Appendix H for step-by-step explanation of study protocol.)

To ensure that participants consistently reached 90^o of knee flexion in an objective manner, use was made of an iPad (Apple, USA), whereby the athlete’s specific goniometric measurements were superimposed on the screen (see Figure 3.3). This was achieved by fixing the iPad in one position in line with the mid-point of the knee joint. The iPad was placed 2 meters perpendicular to the participant's lower limb to minimise the error of parallax effectively.

Figure 3.3: Apple iPad: Goniometer at 90^0 knee flexion.

Additionally, the fatigue protocol was stopped as soon as participants reported pain in the ACLR knee. There was no limit on the number of squats a participant was required to perform. This fatigue protocol was chosen to simulate activities commonly performed in sports. All participants completed the post-fatigue trials within two minutes after the completion of the fatigue protocol.

PILOT STUDY

A pilot study was carried out to determine the effectiveness of the documentations, testing and fatigue protocol that was to be carried out. According to Fouche and Delport (2005:71), pre-testing helps to validate the accuracy, precision, and appropriateness of the research instrument for purposes of obtaining meaningful and quality information. Also, for providing a reason why a group of participants that met the inclusion criteria were eligible to participate in the pilot study to evaluate the reliability and validity of the whole testing battery and the equipment used. Participants' results from the pilot study were not included in the main study.

3.9 DATA ANALYSIS

To obtain the objectives of this study, the quantitative analysis was performed using statistical software Microsoft Excel® (SAS® 9.4. Cary, NC: SAS Institute Inc.StataCorp. 2021) and Stata Statistical Software: Release 17 (College Station, TX: StataCorp LLC) for the purpose of descriptive and inferential statistical analyses. Once the data was collected, descriptive statistics were computed to analyse the relationship between pre- and post-fatigue test data. Descriptive data is presented as means (95 CI) for categorical data and means (±SD) for normally distributed data. The relationship between the scores were determined using ANOVA and a Chi-square analysis. Significance was accepted at ($p<0.05$). Multivariate analyses of the variance were used to compare knee kinetics and muscle activation patterns between the injured and uninjured knee, pre- and post-fatigue. A qualified statistician based at the Nelson Mandela University was consulted to ensure valid and accurate interpretation of the data. For practical significance of the correlations: if correlation coefficient: <0.30 (weak correlation), 0.30 – 0.49 (moderate correlation), >0.50 (strong correlation).

3.10 ETHICAL CONSIDERATIONS

Approval for this study was sought and granted by the Human Ethics committee at Nelson Mandela University before commencing with the study H20-HEA-HMS-007. Participation in the study was voluntary, and all participants were made aware of this fact before agreeing to participate. All participants were required to sign an informed consent form (Appendix D). The researcher was available to answer any questions / queries prior to signing the consent form. Each participant received a document (Appendix E) prior to signing the informed consent form explaining all the above, as well as details pertaining to the study and participation requirements. Participants were encouraged to ask questions during the data collection process or voice any concerns that arose. Furthermore, all participants were informed that they were allowed to withdraw from the study at any time, without prejudice. All results were treated confidentially during the entire research process. All data sheets were coded, participant names were removed, and all data sheets were stored in a locked filing cabinet at the Potgieter and Pike Biokineticists practice for five years. Injury was a potential risk factor due to the neuromuscular fatigue state, so all necessary precautions were taken to limit the risk of physical harm. This study followed the ethical constructs as per the Belmont report (Vitak, Shilton, & Ashktorab, 2016:941).

3.11 CHAPTER SUMMARY

To summarise, a quantitative, descriptive, cross-over research design was used to determine knee joint competence post anterior cruciate ligament reconstruction in amateur SWD rugby players. Fifteen participants were included in the study as they m*et al*l the inclusion criteria. The data collections were done at the Potgieter & Pike Biokinetics practice in George, Western Cape, South Africa. Ethical clearance had been obtained and all ethical guidelines followed throughout the testing procedure.

Chapter 4 will look at the results of the study that will include the descriptive and demographic data. The chapter will go on to describe ACL reconstruction parameters in terms of dominant vs recessive leg and playing position in addition this chapter will look at dynamic stability scores and knee joint muscle activation levels in the injured and uninjured lower limbs, pre- and post-fatigue.

CHAPTER 4

RESULTS

4.1 INTRODUCTION

Chapter four reports the results obtained from the data collection. These results have been reported as descriptive and inferential statistics. All descriptive results are conveyed in-text as the mean ± standard deviation (SD), whereas inferential statistics are reported to 95CI. The results will be unpacked as follows: firstly, demographic information, secondly, injured vs uninjured VMO and VL muscle activation, pre- and post-fatigued in eight SEBT directions and, lastly, injured vs uninjured lower limb SEBT scores, pre- and post-fatigue in eight SEBT directions. Associations between demographic factors and type of behaviour were tested using a Chi square test. Paired sample t-tests were used to compare the different variables for the one group namely the rugby players with ACLR.

4.2 STUDY SAMPLE DESCRIPTION

4.2.1 Participant demographics

The participants had a mean age of 27±3 years, a mean height of 180.65±4.46 cm, a mean weight of 99.5±13.2 kg. The mean number of months post ACLR was 28±2. Table 4.1 below outlines the demographic variables for the study sample.

Table 4.1 Participant demographics (n=15)

Variable	Mean (SD)	Min: Max	IQR Range [Q1:Q3]
Age (yrs.) *	27.2±2.7	20:30	10 [25.5:30]
Height (cm) *	180.65±4.46	175:194	19 [178.5:181.3]
Weight (Kg) *	99.54±13.18	69.1:123.9	54.8 [93.5:106.5]
Months post ACL reconstruction*	28.2±2.83	24:34	10 [26:29.5]
Years playing rugby*	13.3 ± 2.7	8:16	8 [12.5:15]

*Data normally distributed; IQR=interquartile range; Yrs.=years; Min=Minimum; Max=Maximum; SD=Standard Deviation.

Prior to analysing data, the data was evaluated for normality using the Shapiro-Wilk test. All data was normally disturbed. As the complete study sample had medical clearance from their respective team doctors, and all tests were fully completed, all 15 players were included in the final data analysis (n=15).

In addition to reported descriptive and demographic data, the study went on to describe ACL reconstruction parameters, in terms of dominant vs. recessive leg, playing position ACLR percentage SEBT and EMG score between the injured and uninjured leg pre- and post-fatigue.

4.2.2 ACL injury and reconstruction specific descriptive data

In this section, ACL injury and reconstruction specific results related to leg dominance and playing position are discussed. Figure 4.1 shows that the dominant side injuries were 60 percent more prevalent when compared to non-dominant side injuries (40%). In the study sample this translated to nine players exhibiting pathology on the dominant leg.

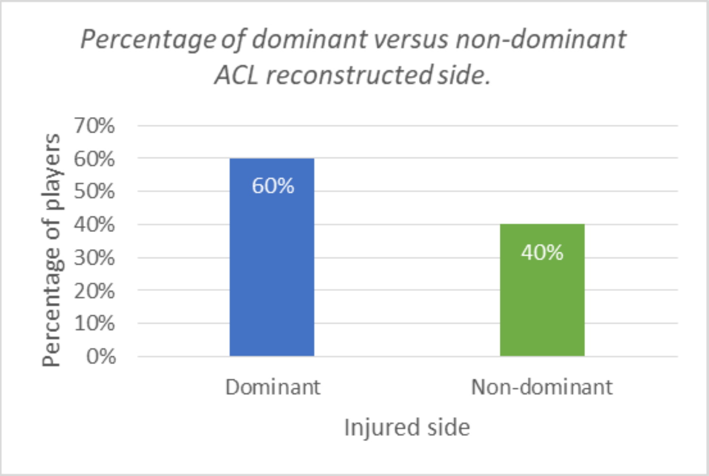


Figure 4.1: Percentage of dominant versus non-dominant ACL reconstructed side

Figure 4.2 graphically illustrates the playing positions of the study cohort and the respective incidence of ACLR surgery. The *flanker* position was the most prevalent player position to have received ACL reconstruction surgery, followed by the *lock*, *scrumhalf*, and *prop*. In this study cohort the *wing* and *flyhalf* showed the least risk for receiving ACL reconstruction surgery.

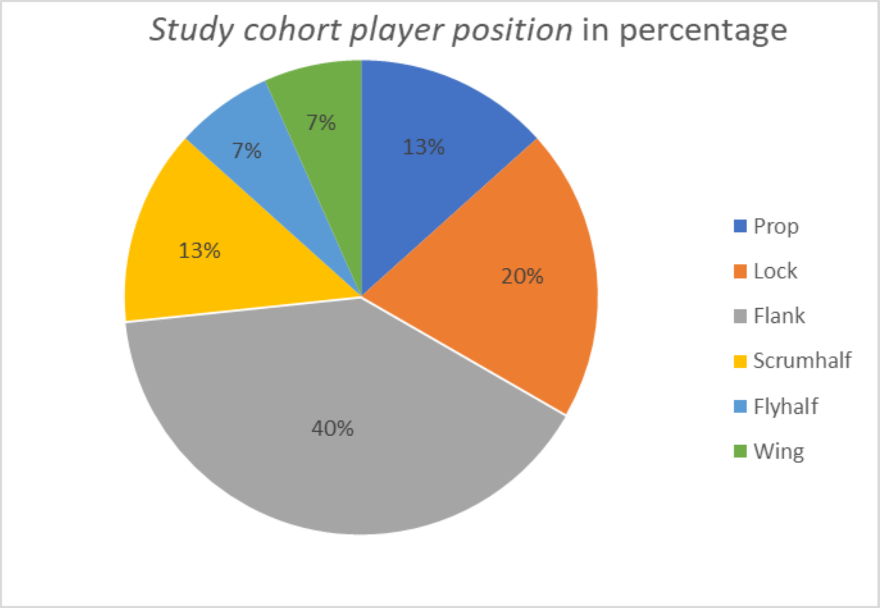


Figure 4.2: Study cohort player position presenting with ACLR surgery.

4.2.3 *VL* and *VMO* injured vs uninjured muscle activation.

The specific role of the VMO is to stabilise the patella within the patella groove, whereas the VL works with the other *quadriceps* muscles to help extend the knee joint (Dewan, Web, Prakash, Malik, Gella & Kipps, 2020:71). The VMO and VL are additionally active in maintaining thigh and patella position while walking and running (Mirzaie, Rahimi, Kajbafvala, Manshadi, Kalantari & Saidee, 2019:55). Therefore, these two muscles are key in ACL reconstruction rehabilitation and return to competitive play. The results for VMO and VL muscle activation was achieved using EMG technology during the SEBT on both the injured and uninjured limbs in a fatigued and a non-fatigued state. Table 4.2 reports this data.

Table 4.2: Paired sample statistics for VL and VMO muscle activation during the SEBT (injured vs uninjured leg in a fatigued and non-fatigued state

Paired Sample Statistics for VL and VMO muscle activation (μV) during the SEBT (injured vs uninjured leg in a fatigue and a non-fatigue state) (n=15)

SEBT Direction	**Muscle**	Mean (SD)			
		Non-fatigue		Fatigued	
		Injured	Uninjured	Injured	Uninjured
Anterolateral	VMO	156.92±71.53	164.11±71.31	232.26±161.85	259.79±97.36
	VL	154.97±59.93	165.05±93.11	226.29±133.06	235.91±110.06
Anterior	VMO	250.03±120.22	283.89±101.10	312.03±150.69	311.01±101.05
	VL	247.23±90.06	280.01±102.25	282.52±120.59	293.17±113.75
Anteromedial	VMO	250.63±130.41	300.57±100.95	343.45±173.43	363.00±118.94
	VL	246.95±99.00	284.20±97.92	305.01±123.56	321.41±116.97
Medial	VMO	273.17±164.82	318.55±85.64	397.51±212.83	354.28±83.70
	VL	261.36±123.53	296.53±96.08	351.76±168.55	320.82±72.05
Posteromedial	VMO	269.98±167.64	271.41±50.07	362.66±196.63	347.17±111.91
	VL	254.25±109.82	251.11±59.57	333.73±158.19	310.97±90.24
Posterior	VMO	254.53±111.47	274.67±72.53	366.02±201.16	323.62±127.68
	VL	250.01±87.50	249.66±54.85	330.44±141.91	296.24±106.72
Posterolateral	VMO	275.83±137.67	251.83±60.15	359.02±216.71	366.87±164.82
	VL	261.85±96.82	241.15±65.60	332.31±154.50	327.04±134.82
Lateral	VMO	244.47±103.10	285.15±94.88	334.17±133.50	353.30±155.87
	VL	241.10±80.06	251.73±85.96	301.27±98.09	312.93±141.23

As indicated in Table 4.2, the highest mean for injured non-fatigued VMO muscle activation was 275.83±137.67μV in the posterolateral direction, compared to the highest mean for injured fatigued VMO muscle activation of 397.51±212.83μV in the medial direction. The lowest mean for injured non-fatigued VMO muscle activation was 156.92±71.53μV in the anterolateral direction, compared to the lowest mean injured fatigued VMO muscle activation of 232.26±161.85μV in the anterolateral direction.

The highest mean for uninjured, non-fatigued VMO muscle activation was 318.55±85.64 µV in the medial direction, compared to the highest mean uninjured, fatigued VMO muscle activation of 366.87±164.82 µV in the posterolateral direction. The lowest mean for uninjured, non-fatigued VMO muscle activation was 164.11±71.31 µV in the anterolateral direction, compared to the lowest mean uninjured fatigued VMO muscle activation of 259.79±97.36 µV in the anterolateral direction. These results can be seen in Table 4.2.

The highest mean for injured, non-fatigued VL muscle activation was 261.85±96.82 µV in the posterolateral direction, compared to the highest mean injured, fatigued VL muscle activation of 351.76±168.55 µV in the medial direction. The lowest mean injured, non-fatigued VL muscle activation was 154.97±59.93 µV in the anterolateral direction, compared to the lowest mean injured, fatigued VL muscle activation of 226.29±133.06 µV in the anterolateral direction.

The highest mean uninjured, non-fatigued VL muscle activation was 296.53±96.08 µV in the medial direction, compared to the highest mean uninjured, fatigued VL muscle activation of 327.04±134.82 µV in the posterolateral direction. The lowest mean uninjured, non-fatigued VL muscle activation was 165.05±93.11 µV in the anterolateral direction, compared to the lowest mean uninjured fatigued VL muscle activation of 235.91±110.06 µV in the anterolateral direction.

Therefore, this data indicates that both injured and uninjured VMO and VL muscles had the least amount of activation in the anterolateral direction pre- and post-fatigue. Additionally, post-fatigue results indicated an increased mean muscle activation of 75.34±90.32 µV in the injured VMO, as well as 95.68±26.05 µV in the uninjured VMO. Similarly, the VL activation mean increased after fatigue by 71.32±73.13 µV on the injured side post fatigue, as well as on the uninjured side by 70.86±16.95 µV in the same direction. Both VMO and VL muscle’s minimum activation in an injured and uninjured state was in the anterolateral direction, and both increased in mean muscle activation from pre- to post-fatigue status.

However, analysis of the maximum muscle activation results differed. In an injured state, both VMO and VL muscles’ maximum activation was in the posterolateral direction and shifted to the medial direction as they were tested under fatigued conditions. This indicated that fatigue on the injured side caused the maximum muscle activation to shift from the posterolateral direction into a more stable medial direction. However, in the uninjured side, the maximum VMO and VL activation in a non-fatigued state was in the medial direction and changed to the posterolateral direction once fatigued. It is also worth noting that both injured and uninjured VMO and VL mean muscle activations increased post-fatigue in all eight SEBT directions.

Table 4.3: Paired sample correlation for VL and VMO muscle activation during the SEBT (injured vs uninjured leg in a fatigued vs non-fatigued state)

Paired Sample Correlation for VL and VMO muscle activation during the SEBT (injured vs uninjured leg in a fatigue vs a non-fatigue state) (n=15)

		Correlation	**P-value**	**Correlation**	**P-value**
SEBT Direction	**Muscle**	Non-fatigue		Fatigued	
		Injured & Uninjured		Injured & Uninjured	
Anterolateral	VMO	0.443	0.098	0.519	0.047*
	VL	0.354	0.195	0.576	0.025*
Anterior	VMO	0.751*	0.001*	0.568	0.027*
	VL	0.544	0.052	0.498	0.059
Anteromedial	VMO	0.752*	0.001*	0.700	0.004*
	VL	0.653	0.008*	0.461	0.084
Medial	VMO	0.734	0.002*	0.746	0.001*
	VL	0.527	0.044*	0.715	0.003*
Posteromedial	VMO	0.039	0.891	0.831*	0.000*
	VL	-0.039	0.891	0.686	0.005*
Posterior	VMO	0.577	0.024*	0.728	0.002*
	VL	0.321	0.244	0.662	0.007*
Posterolateral	VMO	0.464	0.081	0.781*	0.001*
	VL	0.196	0.484	0.762*	0.001*
Lateral	VMO	0.735	0.002*	0.777*	0.001*
	VL	0.625	0.013*	0.660	0.007*

*Significant value

Table 4.3 provides the correlation between the uninjured and injured leg for both the VL and VMO muscle activation respectively in the non-fatigued and fatigued state during SEBT. In the non-fatigued state for VMO activation only three and for VL activation only five SEBT directions were not significantly correlated. In the fatigued state non-significant correlations were only found for VL activation in two SEBT directions. However when correlation effect size criteria are considered only two SEBT directions for VL and one for VMO activation in the non-fatigued state, reflected no correlation.

An independent t-test was conducted to compare the average microvolt production of the VMO and VL in the injured side when fatigued, to the VMO and VL of the uninjured side when fatigued in eight directions of a SEBT (see Table 4.4). There was a significant difference in the muscle activation scores for non-fatigued VMO injured side 250.63±130.41 μV, and non-fatigued VMO uninjured side in an anteromedial direction 300.57±100.95 μV; t (14) = -2.25, p = 0.041. Also, there was a significant difference in the muscle activation scores for non-fatigued VMO injured side 244.47±103.10 μV, and non-fatigued VMO uninjured side in a lateral direction 40.68±72.50 μV; t (14) = -2.17, p = 0.047.

Table 4.4: Paired sample t-test results of comparative data for average VL and VMO muscle activation (µV) during the SEBT (injured vs uninjured leg in the fatigued and the non-fatigued limb) (n=15)

Paired Samples Test (df=14)											
SEBT Direction	**Muscle**	**Injured & Uninjured**					**Injured & Uninjured**				
		Non-fatigue					**Fatigued**				
		Mean (SD)	95% Confidence Level of Difference		*t*	Sig.(2-tailed)	Mean (SD)	95% Confidence Level of Difference		*t*	Sig.(2-tailed)
			Lower	Upper				Lower	Upper		
Anterolateral	VMO	-7.19 (75.36)	-48.926	34.540	-0.370	0.717	-27.53 (139.00)	-104.509	49.443	-0.767	0.456
	VL	-10.08 (91.15)	-60.558	40.398	-0.428	0.675	-9.62 (113.76)	-72.621	53.381	-0.328	0.748
Anterior	VMO	-33.86 (80.1)	-78.218	10.498	-1.637	0.124	1.01 (124.96)	-68.185	70.211	0.031	0.975
	VL	-11.72 (73.32)	-65.458	32.732	-1.462	0.083	-10.65 (117.56)	-75.749	54.456	-0.351	0.731
Anteromedial	VMO	-49.93 (85.96)	-97.534	-2.333	-2.25	0.041*	-19.55 (123.82)	-88.121	49.015	-0.612	0.551
	VL	-37.25 (82.05)	-82.685	8.191	-1.758	0.101	-16.41 (125.03)	-85.644	52.831	-0.508	0.619
Medial	VMO	-45.39 (117.39)	-110.393	19.62	-1.497	0.156	43.23 (160.44)	-45.619	132.072	1.044	0.314
	VL	-35.17 (109.46)	-95.792	25.446	-1.244	0.234	30.94 (127.41)	-39.618	101.498	0.941	0.363
Posteromedial	VMO	-1.43 (173.09)	-97.279	94.426	-0.032	0.975	15.49 (120.86)	-51.439	82.426	0.496	0.627
	VL	3.14 (126.94)	-67.158	73.438	0.096	0.925	22.77 (116.50)	-41.75	87.284	0.757	0.462
Posterior	VMO	-20.14 (91.43)	-70.773	30.493	-0.853	0.408	42.4 (139.11)	-34.635	119.435	1.18	0.257
	VL	0.35 (87.10)	-47.885	48.578	0.015	0.988	34.2 (107.10)	-25.11	93.51	1.237	0.237
Posterolateral	VMO	24.01 (121.99)	-43.551	91.565	0.762	0.459	-7.85 (135.41)	-82.834	67.141	-0.224	0.826
	VL	20.7 (105.78)	-37.88	79.28	0.758	0.461	5.27 (101.47)	-50.919	61.465	0.201	0.843
Lateral	VMO	-40.68 (72.50)	-80.83	-0.53	-2.173	0.047*	-19.13 (99)	-73.951	35.698	-0.748	0.467
	VL	-10.63 (72.07)	-50.537	29.284	-0.571	0.577	-11.67 (106.16)	-70.454	47.121	-0.426	0.677

*Significant value

4.2.4 Injured vs uninjured star excursion balance test score pre- and post-fatigue

The SEBT score was obtained during the SEBT. This test was done on both the injured and uninjured limbs in a non-fatigued and fatigued state. Table 4.5 indicates that the lowest mean SEBT score for injured, non-fatigued lower limb was 55.50±13.13% in the anterolateral direction, compared to the lowest mean SEBT score for uninjured, non-fatigued lower limb of 51.94±11.07%, also in the anterolateral direction. The lowest mean SEBT score for the injured, fatigued lower limb was 58.89±15.27% in the anterolateral direction, compared to the lowest mean uninjured, fatigued SEBT score of 53.99±11.26% correspondingly in the anterolateral direction.

The highest mean SEBT score for injured, non-fatigued lower limb was 85.52±15.19% in the posterior direction, compared to the highest mean SEBT score for uninjured non-fatigued lower limb of 85.28±11.67%, also in the posterior direction. The highest mean SEBT score for the injured, fatigued lower limb was 93.51±13.62% in the posterior direction, compared to the highest mean uninjured, fatigued SEBT score of 88.81±12.81% congruently in the posterior direction, as demonstrated in Table 4.5.

Investigating the muscle activation patterns pre- and post-fatigue, the pattern changes when looking purely at SEBT scores. Similarly, to the mean muscle activation scores, the SEBT's lowest mean scores for the injured and uninjured, pre-, and post-fatigue lower limbs, were all in the anterolateral direction. However, contrary to the muscle activation pattern, the maximum SEBT scores for injured and uninjured, pre– and post-fatigue lower limbs, were all in the posterior direction.

It must be noted that the injured and uninjured lower limb's mean SEBT scores were higher in all 8 directions post fatigue. Additionally, all eight post-fatigue directional scores on the injured side were higher than the uninjured side.

Table 4.5: Paired sample distribution of the 8 directions of the mean SEBT scores (%) produced by the injured and uninjured lower limb, pre- and post-neuromuscular fatigue in amateur SWD rugby players (n=15).

Paired Sample Statistics for injured vs uninjured and fatigue and non-fatigued lower limb during the SEBT (n=15)				
SEBT Direction	**Mean (SD)**			
	Injured	Uninjured	Injured	Uninjured
	Non-fatigued		Fatigued	
Anterolateral	55.50 (13.13)	51.94 (11.07)	58.89 (15.27)	53.99 (11.26)
Anterior	65.91 (10.56)	68.72 (11.46)	69.86 (11.53)	68.64 (11.75)
Anteromedial	70.33 (9.83)	70.65 (8.63	74.02 (11.14)	72.86 (8.75)
Medial	77.50 (9.55)	76.61 (8.90)	81.82 (10.49)	78.22 (11.12)
Posteromedial	84.85 (13.31)	81.79 (10.02)	89.37 (11.70)	86.11 (10.98)
Posterior	85.52 (15.19)	85.28 (11.67)	93.51 (13.62)	88.81 (12.81)
Posterolateral	78.64 (11.53)	78.28 (6.64)	84.16 (11.14)	83.43 (8.72)
Lateral	61.48 (12.43)	64.84 (7.69)	69.53 (12.87)	69.00 (10.98)

Table 4.6 portrays the χ^2 correlations that examined the relationships between uninjured and injured, non-fatigued SEBT scores in all eight SEBT directions. In a non-fatigued state, seven out of a possible eight (86%) SEBT directions showed statistically significant ($p < 0.05$) correlations where the anteromedial and posterior directions both achieved strong positive correlations whereas the anterolateral, anterior, medial, posteromedial, and posterolateral directions all showed strong positive correlations. The anteromedial direction achieved the strongest correlation with a positive relationship, t (14) = 0.878, *p* =0.000.

In a fatigued state, all eight SEBT directions, except for the lateral direction, showed statistical significance ($p < 0.05$) with strong correlations. The anterior direction achieved the strongest correlation with a positive relationship t (14) = 0.777, *p* =0.001 as seen in Table 4.6.

Table 4.6. Chi-square correlations between the SEBT scores produced by the injured and uninjured lower limbs in the 8 directions of the SEBT pre- and post-neuromuscular fatigue in amateur SWD rugby players with ACLR (n=15).

	Paired Sample Correlation (n=15)			
SEBT Direction	**Correlation**	**P-value**	**Correlation**	**P-value**
	Non-fatigued		Fatigued	
	Injured & Uninjured		Injured & Uninjured	
Anterolateral	0.766	0.001*	0.706	0.003*
Anterior	0.595	0.019*	0.777	0.001*
Anteromedial	0.878	0.000*	0.735	0.002*
Medial	0.705	0.003*	0.722	0.002*
Posteromedial	0.724	0.002*	0.573	0.026*
Posterior	0.863	0.000*	0.714	0.003*
Posterolateral	0.740	0.002*	0.718	0.003*
Lateral	0.153	0.586	0.483	0.068

*Significant value

An independent two-tailed t-test was conducted to compare the injured and uninjured mean SEBT scores in all eight directions, pre- and post-neuromuscular fatigue as displayed in Table 4.7. There was no statistical significance found in any direction.

Table 4.7: Independent two-tailed t-test results of the comparison between the injured and uninjured SEBT scores (cm) in all 8 directions pre- and post-neuromuscular fatigue in amateur SWD rugby players with ACLR (n=15).

Paired Samples Test (df=14)										
SEBT Direction	Injured & Uninjured					Injured & Uninjured				
	Non-fatigue					Fatigued				
	Mean (SD)	95% Confidence Level of Difference		*t*	Sig.(2-tailed)	Mean (SD)	95% Confidence Level of Difference		*t*	Sig.(2-tailed)
		Lower	Upper				Lower	Upper		
Anterolateral	3.56 (8.50)	-1.15	8.27	1.62	0.13	4.89 (10.83)	-1.11	10.89	1.75	0.10
Anterior	-2.81 (9.95)	-8.32	2.70	-1.10	0.29	1.21 (7.78)	-3.09	5.52	0.60	0.56
Anteromedial	-0.32 (4.71)	-2.93	2.28	-0.27	0.80	1.16 (7.57)	-3.04	5.35	0.59	0.56
Medial	0.89 (7.12)	-3.06	4.83	0.48	0.64	3.60 (8.08)	-0.88	8.07	1.73	0.11
Posteromedial	3.07 (9.19)	-2.02	8.16	1.29	0.22	3.26 (10.50)	-2.55	9.08	1.20	0.25
Posterior	0.24 (7.80)	-4.08	4.56	0.12	0.91	4.69 (10.03)	-0.86	10.25	1.81	0.09
Posterolateral	0.36 (7.99)	-4.06	4.78	0.17	0.86	0.72 (7.79)	-3.59	5.04	0.36	0.72
Lateral	-3.36 (13.58)	-10.88	4.16	-0.96	0.35	0.53 (12.24)	-6.25	7.30	0.17	0.87

4.3 CHAPTER SUMMARY

The results of this study can be summarised as follow: the VMO muscle showed the highest activation both pre- and post-fatigue, compared to the VL muscle. Both VL and VMO muscle activation increased in all eight SEBT directions post-fatigue. Both injured and uninjured VL and VMO muscles had the lowest activation in the anterolateral direction pre- and post-fatigue. The VL and VMO muscles in the injured limb showed the highest activation pre-fatigue in the posterolateral direction, compared to the uninjured lower limb where the highest activation was observed in the medial direction.

However, when fatigued, an inverse effect occurred where the injured lower limb showed the highest activation in the medial direction, and the uninjured lower limb the highest activation in the posterolateral direction. The SEBT scores for both injured and uninjured lower limbs had the lowest scores in the anteromedial direction pre- and post-fatigue. Comparably, the SEBT scores for both injured and uninjured lower limbs had the highest scores in the posterior direction.

Chapter 5 will discuss the results, as well as how they compare to previous literature in the field. The discussion will unpack a relationship between knee joint muscle activation and dynamic stability test values, in injured and uninjured lower limbs when participants were in a fatigued or non-fatigued state.

CHAPTER 5

DISCUSSION

5.1 INTRODUCTION

The researcher set out to investigate the effect of lower limb neuromuscular fatigue in VMO and VL muscle activation, as well as dynamic stability scoring between the injured and uninjured lower limbs of amateur SWD rugby players who underwent ACL reconstruction surgery. Therefore, this chapter discusses the results of amateur SWD rugby players' VMO and VL muscle activation during a dynamic stability test, pre- and post-fatigue between the injured and uninjured lower limbs. Additionally, this chapter discusses the SEBT scores of amateur SWD rugby players between the injured and uninjured lower limbs, pre- and post-fatigue.

The fatigue protocol used in the study was informed by three key components. Firstly, evidence by Borotikar, Newcomer, Koppes and McLean, (2008:82), who reported that to maintain a fatigue state, extremity neuromuscular fatigue must be induced and maintained. Secondly, studies by Nunley, Wright, Renner, Yu, and Garrett (2003:174), who showed that localised fatigue of *quadriceps* and *hamstring* muscle groups could be achieved through repetitions of isometric and / or eccentric activations. Lastly, this fatigue exercise protocol was unique, as it simulated a similar type of anaerobic fatigue in an individualised manner to each rugby player. In addition, the current fatigue protocol has been used previously, in practice, by the researcher as a Biokineticist during the rehabilitation process of rugby player injuries. These three concepts informed the development of the fatigue protocol used in the study. Therefore, the fatigue protocol used for this study was designed to induce volitional exhaustion with eight repetitive maximum single leg jumps, followed by eight repetitions of single leg squats to 90° repeating this cycle until told to stop by the researcher.

The current study results were in alignment with research by Baker, Kostov, Miller and Weiner (1993:2295), who noted that the decreased performance in the task of interest is commonly used as an indicator of fatigue. The current study showed fatigue had been achieved by a decrease in dynamic stability performance which in this study was measured by muscle activation and balance during the SEBT. This association was reported due to the difficulty in measuring volitional exhaustion directly. To support Baker *et al*., (1993), a significant loss in balance, not reaching 90° knee flexion for five consecutive jumps or squats, or not staying on the beat of the metronome for five consecutive beats for all the subjects and tasks in the post fatigue test in this study, suggested that the fatigue protocol in this study effectively created the desired lower limb neuromuscular fatigue needed to assess whether fatigue could significantly change knee joint kinematics.

5.2 FINDINGS AND RESULTS OUTLINED

This discussion begins with a critical appraisal of dominant vs non-dominant lower limb ACL injuries, position specific ACL injuries, injured vs uninjured lower limb muscle activation, pre- and post-fatigue and SEBT scores, pre- and post-fatigue.

5.2.1 Dominant and non-dominant lower limb ACL injuries

The possible link between leg dominance and ACL injury risk is a debated subject in literature. DeLang, Salamh, Farooq, Tabben, Whiteley, Van Dyk and Charmari (2021:30) proved evidence that soccer players are 1.6 times more likely to injure the dominant limb. In addition, DeLang *et al.,* (2021:30), further suggested that when classifying risk of injury across playing levels, amateurs are 2.6 times more likely to injure the dominant lower limb. In contrast to the results of this study which showed that more ACL injuries occurred on the dominant leg, Dos'Santos, Bishop, Thomas, Comfort and Jones (2019:181) stated in their systematic review that there are no substantial differences in lower limb dominance.

The results of the current study have concluded that only 60 percent of the participants in this study had suffered an ACL injury on their dominant lower limb, concluding that there was no significant observational difference between whether the dominant or non-dominant lower limb was more prone to ACLR. To add to the variability of reports on leg dominance in lower limb injury, there are variables specific to the study methodology that must be considered. Amongst these variables for the current study, was the focus on dominant vs non-dominant lower limb injury sites, and the specific study cohort being limited to amateur SWD rugby players, with previous ACL injuries.

5.2.2 Player position and anterior cruciate ligament injury risk

Focusing on position specific injury rates in rugby players, Falkenmire, Manvell, Callister, and Snodgrass (2020:565) concluded that 55 percent of all injuries were sustained by forwards, and 45 percent by backs. They further narrowed it down and stated that 19 percent of all injuries occurred to second row players, followed by 13.5 percent to wings.

The findings of the current research study were similar for second row players being at 20 percent higher risk of ACL injury than the rest of the positions. Additionally, the current study reported that in the cohort of players with ACL injuries, 40 percent played in the back row forwards more specifically, flank position. The scrumhalf, flyhalf and wings made up 27 percent of the injury risk. These findings of back row forwards (loose forwards) being the most prevalent injury risk position, are supported by literature by Falkenmire *et al*., (2020:565) and Lindsay *et al*., (2015:485). Furthermore, Lindsay, Draper, Lewis, Gieseg and Gill, (2015:485) stated that it is the loose forward trio coupled with inside and outside backs who have the highest work rate and energy expenditure per game with the loose forwards having the highest contact rate. Evidence portrays that there is a direct link between tackle frequency, impact and injury risk (Burger, Lambert & Hendricks, 2020:3).

However, a Rugby World Cup 2019 injury surveillance study by Fuller, Taylor, Douglas and Raftery (2020:2) noted that second row players had the highest mean values when it came to age, height and weight of all players. This has not yet successfully been linked to any higher risk of ACL injury such as the tackle frequency but is a worthy point of future research as they are most of the time in the top three positions linked to injuries as seen once again in this study.

Quarrie, Hopkins, Anthony, and Gill (2013:355) concluded that forwards sustained a considerably greater degree of contact than backs. This statement should be considered with the creation of rehabilitation, recovery, and training programmes during off-, pre- and in-season. Hence why these training phases should look at better contact technique training as well as conditioning and recovery from contact phases for these specific players. The uniformity in reported results should be noted, as this study cohort was limited to amateur SWD rugby team players and not representative of the league at large.

5.2.3 The effect of fatigue on injured and uninjured *vastus medialis obliques* and *vastus lateralis* muscle activation

Current literature suggests that repeated stretch-shortening movements such as cutting, tackling, jumping, and sprinting elicits fatigue in rugby athletes (Wiggins, Grandhi, Schneider, Stanfield, Webster & Myer, 2016:1861). An additional intrinsic modifiable risk, and possibly the most important risk factor, is the effect that neuromuscular fatigue has on the competency of the knee joint, specifically the ACL (Staiano, Bosio, de Morree, Rampinini & Marcora, 2018:175). After inducing fatigue on the lower legs, authors concluded that fatigued athletes show altered motor control strategies, meaning that there are large amounts of strain on the ACL, increasing the anterior tibial shear force and overall risk of non-contact ACL injuries (Chappell, Herman, Knight, Kirkendall, Garrett & Yu, 2005:1022).

The metabolic changes that directly accompany fatigue affect the contractile pathways and activate afferents, which may induce a reduction in force. Factors, such as depletion of ATP levels and neurotransmitter reserves, increased concentration of inorganic phosphates at the cross-bridge level, increased hydrogen ion concentration, decreased intracellular potassium ion concentration, increase in extra cellular potassium ion and increased threshold of synaptic or motor end plate receptors, all lead to the decline in muscle performance capacity (Sharma, 2017:13; Matvienko *et al*., 2017; Staiano *et al*., 2018:175). With diminished knee joint muscle activation knee stability and control could be negatively impacted.

Poor neuromuscular control, muscle imbalances and weak core strength, make athletes more susceptible to non-contact type of injuries due to the repetitive loads forced overtime that will ultimately create dysfunctional movement patterns which in turn could cause injury or re-injury (Tee *et al*., 2016:3194; Fuller *et al*., 2017:51). Keeping the main practical implication in mind of wanting to decrease the time of absence away from rugby activities by all players, after an ACL injury, the researcher explored the effects of fatigue on dynamic stability performance. The outcome of which is hoped to contribute to more effective ACL injury preventative training activities as well as rehabilitation interventions after an ACL injury. This could potentially lead to an added decrease in time away from sport after ACL injury for rugby players (Fuller *et al*., 2017:51; Fitzpatrick *et al*., 2018:160; Hind *et al*., 2020:11).

The effect of fatigue on muscle activation in VMO and VL muscles in an injured and uninjured limb, was reported in terms of both minimum and maximum muscle activations. The results of the study indicated that the lowest VMO and VL activation, pre- and post-fatigue, was in the anterolateral direction for both injured and uninjured limbs. The maximum VMO and VL activation was in the posterolateral direction both pre and post fatigue for the injured and uninjured limb. This may imply that altered neuromuscular control when fatigue is present, could present asymmetries in muscle dynamics recurrently (Lonergan *et al*., 2018:238).

To emphasise, this study reported that the maximum pre-fatigue VMO and VL muscle activation for the injured lower limb was in the posterolateral direction, and the maximum pre-fatigue VMO and VL activation for the uninjured lower limb was in the medial direction. Inversely, the maximum post-fatigue VMO and VL muscle activation for the injured was in the medial direction, and the maximum post-fatigue VMO and VL activation for the uninjured was in the posterolateral direction. Reporting literature on this specified avenue of research in a streamlined cohort, has shown that research on the change of knee joint muscle activation during a dynamic stability movement is lacking when looking at ACL re-injury rates. However, Norris and Trudelle-Jackson (2011:421) concluded that the VMO muscle activation does reach more than the 40 percent threshold of MVC, suggesting that the VMO muscle has a strengthening effect in the anterior, medial, and posteromedial direction. Hence, this study would propose strengthening the *quadricep* muscles in the anterior, medial and posteromedial direction research as a recommendation for future research. As research by Lonergan *et al*., (2018:236) has indicated improvements in knee joint competence with MVC in the anterior, medial and posteromedial directions, this could translate positively to ACL injured rugby players thereby potentially decreasing re-injury rates.

5.2.4 ***Vastus medialis obliques*** **and** ***vastus lateralis*** **muscle activation during SEBT in an injured vs uninjured limb**

Knowing that proprioception plays the most important role in joint function by which the body can vary muscle activation in immediate response to incoming information regarding external forces (Sharma, 2017:13), this study investigated these varying muscle activations paired with knee proprioception changes due to an external factor of neuromuscular fatigue. Literature has shown that bilateral, stable surface lower limb movement, such as the squat, the VL muscle has a higher average activation than the VMO (Choi & Lee, 2017:1950). However, when looking at a unilateral stable surface movement such as the forward lunge, the VMO has the highest average muscle activation (Khaiyat, & Norris, 2018:644). The anterior and posterior directions of the SEBT is performed in a similar fashion as the forward lunge motion, therefore there would be a theoretical expectation of greater VMO activation.

However, the results were similar in all eight directions of the SEBT, where the VMO muscle had the highest average observed activation in all but the anterolateral direction. The current study results in the pre-fatigued state seems to supply some support for a study by Choi and Lee (2017:1950), where researchers also reported the highest activation levels for the VMO muscle during a forward lunge motion at an ankle joint angle of 60°, when compared to all *quadriceps* muscles. It must be acknowledged that none of the observed differences in injured vs uninjured limb comparisons were statistically significant except for the higher VMO activation values in the uninjured limb in two SEBT directions, namely anteromedial and lateral.

In rugby, where the main purpose is to enter the opponent's territory to score points, victory could rely on the ability of a player to make rapid directional changes (cutting and pivoting), be it to prevent attacking movements or, to avoid defenders. Therefore, it is important to know how the knee joint muscle activation react to rapid directional changes, pre- and post-fatigue (Barnett *et al*., 2016:1663). Additionally, the athlete's precision of the knee joint position sense will deteriorate after anaerobic lactic acid exercise (Romero-Franco *et al*., 2014:205). This implied that the SEBT directions that did not show an increase in VMO muscle activation post-fatigue (posterolateral, lateral, anterolateral, and anteromedial) in this study, should be observed as a focus point during clinical exercise prescription, with the main focus on resistance training in those directions to obtain the desired increase in motor unit firing rate in the VMO post-fatigue, which is slightly different to a study by Herrington, Hatcher, Hatcher and McNichols (2009:150), concluding that patients with ACL deficiency had a significantly lower reach in the anterior, lateral, posteromedial and medial directions, compared to healthy individuals.

Furthermore, when investigating the effect that fatigue had on the injured vs uninjured leg, it is noticeable that three directions had substantial observational increases in the correlation values. As most directions had a statistically significant *p*-value, the researcher mainly focused on directions which had both strong correlation as well as statistically significant *p*-value. The posteromedial, posterolateral, and lateral directions ended with a very high positive correlation and statistical significance, specifically when looking at the correlation of the VMO muscle activation between the injured and uninjured lower limb. Indicating that these three directions were the only directions where there was a statistically significant increase in the difference between the injured vs uninjured VMO muscle activation, with a high association from pre-fatigue to a post-fatigue state, creating a possible high-risk direction for possible re-injury. Dobija, Reynaud, Pereira, van Hille, Descamps, Bonnin and Coudeyre (2019:11) denoted that the posteromedial and postural directions of the SEBT could be used to detect bilateral neuromuscular control deficits in their study, comparing ACL deficient players with a controlled uninjured group. While the findings of this study suggest potential support to previous literature (Dobija *et al*., (2019) and Choi & Lee 2017), that the posteromedial and posterolateral direction can be used to detect neuromuscular control deficits. Additionally in this study the lateral direction, especially when looking at the difference between the pre-fatigue injured vs uninjured VMO muscle activation and the difference between post-fatigue injured vs uninjured VMO muscle activation paired with SEBT score difference between the uninjured vs injured pre- and post-fatigue condition showed the best statistical significance.

Given these points, the results of this study, with regards to the increase in VMO and VL muscle activation in all eight directions of the SEBT post-fatigue, the results observed suggests the presence of a centralised feed-forward neuromuscular alteration in amateur SWD rugby players with ACL injury. These results support the study of Webster *et al*., (2016:631) who reported that there is a centralised feed-forward neuromuscular adjustment in patients with chronic ankle instability when focusing on ankle-joint muscles and proximal hip muscles activation that increased post-fatigue. Additionally, Dashti Rostami, Alizadeh, Minoonejad, Yazdi and Thomas, (2018:22) reported that VMO activation increases post-fatigue during a bilateral and unilateral lower limb movement.

It is once again emphasised that there is a feed-forward mechanism that forms part of a by-product produced by neuromuscular fatigue. In support of literature published by Dashti *et al*., (2018), this study observed that both the VMO and VL activation increased with fatigue. However, it is also interesting to note that the injured lower limb generally had a larger observed mean activation increase post-fatigue in both VMO and VL of the injured lower limb, compared to the uninjured lower limb. In addition to the aforementioned statement, it is interesting to note that the observed fatigued SEBT scoring had the same effect, as the injured lower limb had the greater observed increase post fatigue compared to the uninjured lower limb.

Additionally, the study results showed noteworthy correlations ($p<0.05$) between the injured and uninjured lower limbs for the anterior, anteromedial, medial, posterior and lateral directions pre-fatigue VMO muscle activation. Meaning that the amount by which the injured VMO activation increased from pre-fatigue to post-fatigue, in these directions could potentially be classified as high-risk directions in injured lower limbs.

These results have implications for post ACL reconstruction rehabilitation and return to play standards. In short, the results of this study on amateur SWD rugby players with previous ACL injuries, enhances the theory of a centralised feed-forward neuromuscular alteration by adding observed anterior knee-joint muscle activation increases, post-neuromuscular fatigue, to the aforementioned author's theory of centralised feed-forward neuromuscular alteration to ankle- and proximal hip-joint muscles.

5.2.5 SEBT scores pre- and post-fatigue

Research suggests that certain components of the SEBT can be used as a reliable predictive measurement for lower limb injurie risk in athletes (Plisky, Rauh, Kaminski, & Underwood, 2006:916). Stiffler *et al*., (2017:342) agreed and asserted that the anterior SEBT direction was the only direction with enough asymmetry to use as a pre-knee injury screening tool in collegiate athletes.

Upon examining the results, it was the anterolateral direction that had the lowest normalised SEBT score during pre- and post-fatigue for both the injured and un-injured lower limbs. On the other hand, the posterior direction showed the maximum reached direction in both injured and uninjured lower limbs for both measure points, pre- and post-fatigue. Gribble and Hentel (2003:95) suggested that for both the anterolateral direction, the minimum and the posterolateral direction for the maximum should be based on normative published data. It is therefore suggested that sport specific SEBT norms be researched not only to be measured against a more specialised norm, but also to be used by Biokineticists and conditioning coaches as a pre-season injury risk screening tool.

The study results showed no notable difference between the minimum excursion reached distance direction and the minimum muscle activation direction, as they are both in the anterolateral direction injured and uninjured lower limb, pre-and post-fatigue. However, there is a noticeable observed difference between the maximum excursion reached distance direction, and the maximum muscle activation direction, for both injured and uninjured lower limbs, pre- and post-fatigue. This means that maximum excursion reach distance is not directly linked to maximum VMO and VL muscle activation, and that fatigue does not affect the maximum excursion reach direction, but only changes the maximum VMO and VL muscle activation between the injured and uninjured lower limb. These results indicate that the Biokineticist or conditioning coach should not only look at one variable, but rather look at the relationship or difference between the maximum reached excursion in a specific direction, as well as the increased difference of injured vs uninjured knee joint muscle activation in conjunction from pre- to post-fatigue in the same direction. Keeping in mind that the muscle activation and excursion distance of a competent knee joint would increase post-fatigue.

To further explore the study results, the researcher looked at the difference between pre-fatigue injured vs uninjured SEBT performance and the difference between post-fatigue injured vs uninjured SEBT performance. Armstrong, Brogden, Milner, Norris and Greig (2018:147) suggested that there was no significant effect on the modified SEBT score when comparing the difference between the dominant and non-dominant lower limbs of dancers, post-fatigue. The current study supports data by Armstrong *et al*., (2018:148) showing that during a pre-fatigued state, the uninjured lower limb's VMO muscle had the highest activation in all eight SEBT directions except the posterolateral direction, compared to the pre-fatigued injured lower limb. Similarly, in a fatigued state, it is observed that the VMO muscle of the injured and uninjured lower limb had the highest activation in seven directions but the non-fatigued uninjured anterolateral direction. These results verify the feedforward neuromuscular adjustment post-fatigue in the injured and un-injured limb, but only in specific directions which is supported by Smeets, Vanrenterghem, Staes, Vandenneucker, Claes and Verschueren, (2020:347).

Therefore, to summarise the comparison between SEBT score differences between injured vs uninjured, pre- and post-fatigue, the study reports that neuromuscular fatigue alters dynamic stability performance, as the observed mean SEBT score in all eight directions of the injured and uninjured limb increased. A statistically significant difference could not be reported in SEBT scores between injured vs uninjured limb in pre- and post-fatigue tests.

Although the results of this study portrayed a non-significant feed-forward mechanism between injured vs uninjured from pre- to post-fatigue with regards to muscle activation and excursion distance, the results still contradict literature by Wild *et al*., (2017:644), and Schroderet, Allet and Hilfiker, (2020) who stated that fatigue has an adverse impact on lower limb dominance, dynamic stability, and neuromuscular control. It must be noted that most literature uses different forms of neuro-muscular fatigue protocols that could be producing different results. The return to a cutting and pivoting sport after an ACL injury increases the athlete's likelihood of a re-injury on the ipsilateral and contralateral lower limbs by five times (Armstrong, Brogden, Milner, Norris and Greig 2018:147). Stating the importance to use every deficit quantity between the injured and un-injured lower limbs from set norms for the knee joint muscle activation and dynamic stability tests during rehabilitation or return to play actions, to determine the likelihood of re-injury (Arundale *et al*., 2018:422). It is advised that a more generalised lower limb neuro-muscular fatigue protocol for all cutting and pivoting sport related knee injury studies is compiled.

5.3 LIMITATIONS

Due to the nature of this study, several limitations were considered.

- Firstly, the sampling procedure focused on a specific set of amateur rugby players, namely those residing in SWD. The findings of the study are therefore limited to the specific sample and are not representative of the rugby player population at large.
- Secondly, the sample size (n=15) was considered a small sample for statistical and methodological design. However, due to the specified inclusion criteria and the condition specific nature, the sample was representative of the amateur SWD rugby player post ACLR.
- Thirdly, due the dynamic physical rehabilitation and sport requirements, there were variations in the phase of ACL rehabilitation amongst study participants.
- Finally, the COVID-19 pandemic in 2020/21, which resulted in varied lockdown restriction, filtered down negatively on the sport and data collection due to time availability.

5.4 RECOMMENDATIONS FOR FURTHER RESEARCH

Upon synthesising the study results and available literature, the following recommendations for future research has been suggested:

i. the effect of fatigue on injured and uninjured VMO and VL muscle activation in a bigger cohort of rugby players, and
ii. a further exploration on the relationship between knee-joint muscle activation and dynamic stability tests, and
iii. the knee joint muscle activation during dynamic rehabilitation exercises to fully understand the physiological changes that the knee joint muscle undergoes after ACLR, and how it should be implemented and tested during rehabilitation and return to play testing, and
iv. as literature denotes that the SEBT can be used to highlight potential risks of re-injury, additional research is recommended on the use of SEBT scores for return to play criteria.

5.5 THEORETICAL AND PRACTICAL IMPLICATIONS

Biokineticists, or any rehabilitation specialist can potentially use this data for sport specific individualised rehabilitation, as well as clearance testing for return to play criteria once the full dynamic of the “menace dynamic direction” term, created by this author, is fully understood. This data will not only assist in the rehabilitation for ACL injury in the rugby realm, but also with continuing clinical trauma associated with ACL reconstruction such as meniscal tears, chondral lesions, and increased risk of early-onset post-traumatic osteoarthritis (Khan *et al*., 2019:965). Once the reliability and validity of this testing has been validated, norms according to sport, positions, sex, age, and race should be looked at to implement in the sporting rehabilitation realm. For example, in SWD amateur rugby players with ACLR, rehab could potentially be fixated more on VMO activation in the anterolateral, anteromedial, posteromedial, and lateral directions in the injured lower limb, post-fatigue. Coherently, focus could potentially be placed on VL activation in the anterolateral, anterior, anteromedial, and lateral directions in the injured lower limb, post-fatigue, when doing dynamic stability rehabilitation with more in-depth research on the topic.

This study implies that the positions identified to be at a high-risk of ACL injury and re-injury should be slightly closer monitored with regards to speed, distance covered and energy expenditure during off-, pre- and in-season at all levels. For example, there should be additional functional movement screening and anterior knee muscle activation correlation between the two lower limbs. This would suggest that a better correlation between the anterior knee muscles activation scores could mean a lower risk for re-injury, during a dynamic stability test for players with previous ACL injury, playing in the high-risk positions or those who are entering a higher-level competition for the first time.

Strength and conditioning coaches could use this data in the future as a potential pre-screening tool to identify any risks and, accordingly do pre-season conditioning, to limit any chances of non-contact re-injury, which could lead to higher player performance plus leading to better rugby club or union performance.

5.6 CHAPTER SUMMARY

The chapter can be summarised in three main points:

Firstly, forwards, specifically back row forwards, had the highest ACL injury rate of all other positions followed by second row forwards. Secondly, the effect of fatigue on an injured and uninjured VMO and VL muscle activation showed that the maximum VMO and VL muscle activation fluctuated more as the injured VMO and VL had the highest activation in the posterolateral direction, and uninjured VMO and VL in the medial direction, pre-fatigue. Inversely, the maximum muscle activation during a fatigued state had the injured VMO and VL activation in the medial direction, and the uninjured VMO and VL activation in the posterolateral direction. The maximum SEBT score for injured and uninjured lower limbs, during pre- and post-fatigue, stayed in the posterior direction, and the minimum SEBT score for injured and uninjured lower limbs, during pre- and post-fatigue, were observed for the anterolateral direction. Fatigue seems to only affect the knee joint muscle activation patterns which, in conjunction with the SEBT, could potentially be linked to pre-screening for a potential risk of re-injury in athletes with more in-depth research.

Therefore, to answer the objectives set for the study the researcher focused on the main outcomes of each objective and then provide a synthesis the objectives together.

Firstly, the main finding for the first objective was that the uninjured VMO muscle activation was significantly higher in seven of the directions pre-fatigue except in the posterolateral direction. Similarly, the uninjured VMO muscle activation was higher in half of the directions namely, anterolateral, anteromedial, lateral and posterolateral directions which indicates the injured VMO was not producing enough activation possibly creating an opportunity for re-injury. The second objective's main finding was that both VMO and VL muscle activation observationally increased after fatigue in all eight SEBT directions. No significant SEBT score differences were noted between the injured and uninjured lower limbs pre-fatigue in all eight SEBT directions was the core finding for the second objective. The third objectives main finding indicated that all the SEBT scores increased after fatigued except for the uninjured limb in the anterior direction. To link these objectives based on the present research, the possibility exists that changes in the quadricep muscle coordination strategies, through SEBT, may cause one or more quadricep muscles to be disproportionately activated, possibly increasing the metabolic demands and thus prematurely fatiguing the overactive muscle which could potentially lead to a risk of re-injury in the injured lower limb.

5.7 CONCLUSION

The study aimed to identify knee joint competence post ACLR in amateur SWD rugby players. The variables were measured on both the injured and uninjured sides. Firstly, the study concludes the VMO and VL muscle activation pre- and post-fatigue is the lowest in the anterolateral direction for the injured and uninjured lower limbs. The maximum VMO and VL muscle activation fluctuated more, as the injured VMO and VL showed the highest activation in the posterolateral direction, and the uninjured VMO and VL the highest activation in the medial direction, pre-fatigue. Inversely, the medial direction had the maximum injured limb VMO and VL muscle activation during a fatigued state, and the uninjured limb VMO and VL activation in the posterolateral direction.

Secondly, the study concludes that the SEBT score showed no statistically significant differences between the injured vs uninjured limb in both pre- and post-fatigued states, ultimately suggesting that these players have been through good forms of rehabilitation post ACLR. The maximum SEBT score for injured and uninjured lower limbs, during pre- and post-fatigue, stayed in the posterior direction, and the minimum

SEBT score for injured and uninjured lower limbs, during pre- and post-fatigue, was achieved in the anterolateral direction. Fatigue seems to only affect the knee joint muscle activation patterns which, in conjunction with the SEBT, could be linked to pre-screening for a potential risk of re-injury in athletes with a more in-depth research strategy.

The execution of all movement and therefor also sport related movement is predominantly influenced by proprioception and may maximise performance and prevent injuries in athletes as it informs the body of position by making use of information from muscles, tendons, joints, as well as the skin (Romero-Franco *et al*., 2014:205). Proprioception plays an important role in maintaining joint stability during dynamic movement and it is critical to restore optimal function after injury to the various tissues that house the relevant receptors such as ligament, particularly the ACL as applicable to this study. It is equally important to objectively assess proprioceptive functioning in order to monitor progress during injury rehabilitation and prevent re-injury.

REFERENCES

Abulhasan, J. F., & Grey, M. J., 2017. Anatomy and physiology of knee stability. *Journal of Functional Morphology and Kinesiology*, *2*(4):34.

Agostini, V., Ghislieri, M., Rosati, S., Balestra, G., & Knaflitz, M., 2020. Surface electromyography applied to gait analysis: how to improve its impact in clinics? *Frontiers in Neurology*, *11(5)*.

Akima, H., Tomita, A., & Ando, R., 2019. Effect of knee joint angle on the neuromuscular activation of the quadriceps femoris during repetitive fatiguing activations. *Journal of Electromyography and Kinesiology*, *49*:102356.

Alazzawi, S., Sukeik, M., Ibrahim, M. & Haddad, F.S., 2016. Management of anterior cruciate ligament injury: pathophysiology and treatment. *British Journal of Hospital Medicine*, *77*(4):222-225.

Alentorn-Geli, E., Alvarez-Diaz, P., Ramon, S., Marin, M., Steinbacher, G., Rius, M., Seijas, R., Ares, O. & Cugat, R., 2015. Assessment of gastrocnemius tensiomyographic neuromuscular characteristics as risk factors for anterior cruciate ligament injury in male soccer players. *Knee Surgery, Sports Traumatology, Arthroscopy*, *23*(9):2502-2507.

Alentorn-Geli, E., Myer, G.D., Silvers, H.J., Samitier, G., Romero, D., Lázaro-Haro, C. & Cugat, R., 2009. Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: Mechanisms of injury and underlying risk factors. *Knee surgery, sports traumatology, arthroscopy*, *17*(7):705-729.

Andrade, R., Pereira, R., van Cingel, R., Staal, J. B., & Espregueira-Mendes, J. 2020. How should clinicians rehabilitate patients after ACL reconstruction? A systematic review of clinical practice guidelines (CPGs) with a focus on quality appraisal (AGREE II). *British journal of sports medicine*, *54*(9):512-519.

Armstrong, R., Brogden, C. M., Milner, D., Norris, D., & Greig, M., 2018. The influence of fatigue on star excursion balance test performance in dancers. *Journal of Dance Medicine & Science*, *22*(3):142-147.

Arockiaraj, J., Korula, R. J., Oommen, A. T., Devasahayam, S., Wankhar, S., Velkumar, S., & Poonnoose, P. M., 2013. Proprioceptive changes in the contralateral knee joint following anterior cruciate injury. *The bone & joint journal*, *95*(2):188-191.

Arundale, A. J., Capin, J. J., Zarzycki, R., Smith, A. H., & Snyder-Mackler, L., 2018. Two-year ACL reinjury rate of 2.5%: outcomes report of the men in a secondary ACL injury prevention program (ACL-SPORTS). *International journal of sports physical therapy*, *13*(3):422.

Austin, D. J., Gabbett, T. J., & Jenkins, D. J., 2011. Repeated high-intensity exercise in a professional rugby league. *The Journal of Strength & Conditioning Research*, *25*(7):1898-1904.

Baker, A. J., Kostov, K. G., Miller, R. G., & Weiner, M. W., 1993. Slow force recovery after long-duration exercise: metabolic and activation factors in muscle fatigue. *Journal of Applied Physiology*, *74*(5):2294-2300.

Barber-Westin, S. D., & Noyes, F. R., 2017. Effect of fatigue protocols on lower limb neuromuscular function and implications for anterior cruciate ligament injury prevention training: a systematic review. *The American journal of sports medicine*, *45*(14):3388-3396.

Barnett, L. M., Lai, S. K., Veldman, S. L., Hardy, L. L., Cliff, D. P., Morgan, P. J., Zask, A., Lubans, D.R., Shultz, S.P., Ridgers, N.D., & Rush, E., 2016. Correlates of gross motor competence in children and adolescents: a systematic review and meta-analysis. *Sports medicine*, *46*(11):1663-1688.

Bastien, M., Moffet, H., Bouyer, L., Perron, M., Hébert, L. J., & Leblond, J., 2014. Concurrent and discriminant validity of the Star Excursion Balance Test for military personnel with lateral ankle sprain. *Journal of Sport Rehabilitation*, *23*(1):44-55.

Benazzouz, A., & Slimane, Z. E. H., 2021. Knee pathology diagnosis based on muscle activation intervals detection and the relationship between knee flexion and surface EMG. *International Journal of Medical Engineering and Informatics*, *13*(1):14-23.

Bencke, J., Aagaard, P. & Zebis, M.K., 2018. Muscle activation during ACL injury risk movements in young female athletes: A narrative review. *Frontiers in Physiology*, *9*:445.

Borotikar, B. S., Newcomer, R., Koppes, R., & McLean, S. G., 2008. Combined effects of fatigue and decision making on female lower limb landing postures: central and peripheral contributions to ACL injury risk. *Clinical biomechanics*, *23*(1):81-92.

Bourne, Matthew, Opar, David A., Williams, Morgan, & Shield, Anthony,.2015. Eccentric knee-flexor strength and risk of *hamstring* injuries in Rugby Union: A prospective study. American Journal of Sports Medicine, 43(11):2663-2670 https://doi.org/10.1177/0363546515599633

Brazier, J., Antrobus, M., Stebbings, G.K., Day, S.H., Heffernan, S.M., Cross, M.J. & Williams, A.G., 2019. Tendon and ligament injuries in elite rugby: The potential genetic influence. *Sports*, *7*(6):138.

Brooks JH, Fuller CW, Kemp SP & Reddin DB., 2005. A prospective study of injuries and training amongst the England 2003 Rugby World Cup squad. *British Journal of Sports Medicine*. 39(5):288- 93.

Brown, A. M., Zifchock, R. A., & Hillstrom, H. J., 2014. The effects of limb dominance and fatigue on running biomechanics. *Gait & posture*, *39*(3):915-919.

Brown, J.C., Verhagen, E., Knol, D., Van Mechelen, W. & Lambert, M.I., 2016. The effectiveness of the nationwide B ok S mart rugby injury prevention program on catastrophic injury rates. *Scandinavian journal of medicine & science in sports*, *26*(2):221-225.

Brown, S. R., Brughelli, M., & Hume, P. A., 2014. Knee mechanics during planned and unplanned sidestepping: a systematic review and meta-analysis. *Sports medicine*, *44*(11):1573-1588.

Brukner, P., Clarsen, B., Cook, J., Cools, A., Crossley, K., Hutchinson, M., McCrory, P., Bahr, R. & Khan, K., 2018. *Brukner & Khan's clinical sports medicine* 1: McGraw-Hill Education.

Bu, D., Guo, S., Ma, H., Xu, H., & Wei, C, 2018. Pattern recognition of continuous elbow joint movements using bispectrum-based sEMG. In *2018 IEEE International Conference on Mechatronics and Automation (ICMA)* (1): 551-556.

Burger, N., Lambert, M., & Hendricks, S, 2020. Lay of the land: narrative synthesis of tackle research in rugby union and rugby sevens. *BMJ open sport & exercise medicine*, *6*(1): e000645.

Campanini, I., Disselhorst-Klug, C., Rymer, W. Z., & Merletti, R., 2020. Surface EMG in Clinical Assessment and Neurorehabilitation: barriers limiting its use. *Frontiers in Neurology*, (*11)*:934.

Carden, P., Bru, B., Jones, A., & Dixon, S., 2017. Influence of rugby surface type and boot stud length on lower limb biomechanical variables associated with Achilles tendinopathy during Rugby Union specific movements. *Footwear Science*, *9*(1):132-134.

Cavaignac, E., Coulin, B., Tscholl, P., Nik Mohd Fatmy, N., Duthon, V., & Menetrey, J., 2017. Is quadriceps tendon autograft a better choice than *hamstring* autograft for anterior cruciate ligament reconstruction? A comparative study with a mean follow-up of 3.6 years. *The American journal of sports medicine*, *45*(6):1326-1332.

Chappell, J. D., Herman, D. C., Knight, B. S., Kirkendall, D. T., Garrett, W. E., & Yu, B., 2005. Effect of fatigue on knee kinetics and kinematics in stop-jump tasks. *The American journal of sports medicine*, *33*(7):1022-1029.

Charles, D., White, R., Reyes, C., & Palmer, D., 2020. A systematic review of the effects of blood flow restriction training on quadriceps muscle atrophy and circumference post ACL reconstruction. *International Journal of Sports Physical Therapy*, *15*(6): 882.

Chavarro-Nieto, C., Beaven, M., Gill, N., & Hébert-Losier, K., 2021. Hamstrings injury incidence, risk factors, and prevention in Rugby Union players: A systematic review. *The Physician and sportsmedicine*, 1:1-19.

Choi, Y., & Lee, S., 2017. Changes in lower limb muscle activity based on angle of ankle abduction during lunge exercise. *Journal of physical therapy science*, *29*(11):1947-1949.

Christensen, J. E., Taylor, N. E., Hetzel, S. J., Shepler, J. A., & Scerpella, T. A., 2017. Isokinetic strength deficit 6 months after adductor canal blockade for anterior cruciate ligament reconstruction. *Orthopaedic Journal of Sports Medicine*, *5*(11):232.

Clark, N. C., & Clacher, L. H. 2020. Lower-limb motor-performance asymmetries in English community-level female field hockey players: Implications for knee and ankle injury prevention. *Physical Therapy in Sport*, *43*:43-51.

Contessa, P., De Luca, C. J., & Kline, J. C. 2016. The compensatory interaction between motor unit firing behaviour and muscle force during fatigue. *Journal of neurophysiology*, *116*(4): 1579-1585.

Corban, J., Lorange, J. P., Laverdiere, C., Khoury, J., Rachevsky, G., Burman, M., & Martineau, P. A. 2021. Artificial Intelligence in the Management of Anterior Cruciate Ligament Injuries. *Orthopaedic Journal of Sports Medicine*, *9*(7):1

Costello, N., Deighton, K., Preston, T., Matu, J., Rowe, J., Sawczuk, T., Halkier, M., Read, D.B., Weaving, D. & Jones, B., 2018. Collision activity during training increases total energy expenditure measured via doubly labelled water. *European Journal of Applied Physiology*, *118*(6):1169-1177.

Cross, M., Kemp, S., Smith, A., Trewartha, G., & Stokes, K., 2016. Professional Rugby Union players have a 60% greater risk of time loss injury after concussion: a 2-season prospective study of clinical outcomes. *British journal of sports medicine*, *50*(15):926-931.

Cummins, C. J., Gray, A. J., Shorter, K. A., Halaki, M., & Orr, R.,2018. Energetic demands of interchange and full-match rugby league players. *The Journal of Strength & Conditioning Research*, *32*(12):3447-3455.

Dashti Rostami, K., Alizadeh, M. H., Minoonejad, H., Yazdi, H., & Thomas, A, 2018. Effect of fatigue on electromyographic activity patterns of the knee joint muscles in anterior cruciate ligament reconstructed and deficient patients during landing task. *Journal of Functional Morphology and Kinesiology*, *3*(2):22.

Delahunt, E., Chawke, M., Kelleher, J., Murphy, K., Prendiville, A., Sweeny, L. & Patterson, M., 2013. Lower limb kinematics and dynamic postural stability in anterior cruciate ligament-reconstructed female athletes. *Journal of athletic training*, *48*(2):172-185.

DeLang, M. D., Salamh, P. A., Farooq, A., Tabben, M., Whiteley, R., van Dyk, N., & Chamari, K., 2021. The dominant leg is more likely to get injured in soccer players: Systematic review and meta-analysis. *Biology of Sport*, *38*(3).

Dewan, V., Webb, M. S. L., Prakash, D., Malik, A., Gella, S., & Kipps, C., 2020. When does the patella dislocate? A systematic review of biomechanical & kinematic studies. *Journal of Orthopaedics*, *20*:70-77.

Diekfuss, J. A., Hogg, J. A., Grooms, D. R., Slutsky-Ganesh, A. B., Singh, H., Bonnette, S., Manish, A., Gary, W., & Myer, G. D., 2020. Can we capitalize on central nervous system plasticity in young athletes to inoculate against injury? *Journal of Science in Sport and Exercise*, (1):1-14.

Di Stasi, S., Myer, G. D., & Hewett, T. E., 2013. Neuromuscular training to target deficits associated with second anterior cruciate ligament injury. *journal of orthopaedic & sports physical therapy*, *43*(11):777-A11.

Disselhorst-Klug, C., Williams, S., & von Werder, S. C., 2018. Surface electromyography meets biomechanics or bringing sEMG to clinical application. In *International Conference on Neurorehabilitation*, 1013-1016.

do Carmo Aprigio, P. S. A., de Jesus, I. R. T., Porto, C., Lemos, T., & de Sá Ferreira, A., 2020. Lower limb muscle fatigability is not associated with changes in movement strategies for balance control in the upright stance. *Human movement science*, *70*:102588.

Dobija, L., Reynaud, V., Pereira, B., Van Hille, W., Descamps, S., Bonnin, A., & Coudeyre, E., 2019. Measurement properties of the Star Excursion Balance Test in patients with ACL deficiency. *Physical Therapy in Sport*, *36*:7-13.

Doherty, C., Bleakley, C.M., Hertel, J., Caulfield, B., Ryan, J. & Delahunt, E., 2015. Laboratory measures of postural control during the star excursion balance test after acute first-time lateral ankle sprain. *Journal of athletic training*, *50*(6):651-664.

Dos'Santos, T., Bishop, C., Thomas, C., Comfort, P., & Jones, P. A., 2019. The effect of limb dominance on change of direction biomechanics: a systematic review of its importance for injury risk. *Physical therapy in sport*, *37*:179-189.

Dubois, R., Paillard, T., Lyons, M., McGrath, D., Maurelli, O., & Prioux, J., 2017. Running and metabolic demands of elite rugby union assessed using traditional, metabolic power, and heart rate monitoring methods. *Journal of sports science & medicine*, *16*(1):84.

Durning, J. V., & Womersley. J., 1974. Body Fat Assessment from Total Body Density and Its Estimation from Skinfold Thickness measurements on 481 Men and Women aged 16 to 72 years. *British Journal of Nutrition*, *32*:77-97.

Duthon, V.B., Barea, C., Abrassart, S., Fasel, J.H., Fritschy, D. & Ménétrey, J., 2006. Anatomy of the anterior cruciate ligament. *Knee surgery, sports traumatology, arthroscopy*, *14*(3):204-213.

Eckenrode, B.J., Carey, J.L., Sennett, B.J. & Zgonis, M.H., 2017. Prevention and management of post-operative complications following ACL reconstruction. *Current reviews in musculoskeletal medicine*, *10*(3):315-321.

Edmonds, W.A. & Kennedy, T.D., 2016. *An applied guide to research designs: Quantitative, qualitative, and mixed methods*. Sage Publications.

Falkenmire, A., Manvell, J., Callister, R., & Snodgrass, S., 2020. Injury incidence, characteristics, and timing in amateur male rugby union: A prospective cohort study (3):565.

Farnan, D., Mahony, N., Wilson, F., & Gissane, C., 2013. A 3-month prospective study of injuries in amateur rugby and soccer. *Physiotherapy Practice and Research*, *34*(2):103-112.

Fitzpatrick, A. C., Naylor, A. S., Myler, P., & Robertson, C., 2018. A three-year epidemiological prospective cohort study of rugby league match injuries from the European Super League. *Journal of science and medicine in sport*, *21*(2):160-165.

Flaxman, T. E., Alkjær, T., Smale, K. B., Simonsen, E. B., Krogsgaard, M. R., & Benoit, D. L., 2019. Differences in EMG–moment relationships between ACL-injured and uninjured adults during a weight-bearing multidirectional force control task. *Journal of Orthopaedic Research*, *37*(1): 113-123.

Flevas, D. A., Bernard, M., Ristanis, S., Moraiti, C., Georgoulis, A. D., & Pappas, E. 2017. Peroneal electromechanical delay and fatigue in patients with chronic ankle instability. *Knee Surgery, Sports Traumatology, Arthroscopy*, *25*(6): 1903-1907.

Fouché, C. B., & Delport, C. S. L., 2005. Introduction to the research process. *De Vos, AS, Strydom, H., Fouché, CB & Delport, CSL*:71-85.

Fraas, M. R., & Burchiel, J., 2016. A systematic review of education programmes to prevent concussion in rugby union. *European journal of sport science*, *16*(8):1212-1218.

Frigo, C., & Crenna, P., 2009. Multichannel SEMG in clinical gait analysis: a review and state-of-the-art. *Clinical Biomechanics*, *24*(3): 236-245.

Fuller, C. W., 2017. A kinetic model describing injury-burden in team sports. *Sports medicine*, *47*(12):2641-2651.

Fuller, C. W., Molloy, M. G., Bagate, C., Bahr, R., Brooks, J. H., Donson, H., Donson, H., Kemp, S.P., McCrory, P., McIntosh, A.S., Meeuwisse, W.H., & Quarrie, K. L., 2007. Consensus statement on injury definitions and data collection procedures for studies of injuries in rugby union. *British journal of sports medicine*, *41*(5):328-331.

Fuller, C. W., Taylor, A., Douglas, M., & Raftery, M., 2020. Rugby World Cup 2019 injury surveillance study. *South African Journal of Sports Medicine*, *32*(1):2

Fuller, C.W., Taylor, A. & Raftery, M., 2018. Eight-season epidemiological study of injuries in men's international Under-20 rugby tournaments. *Journal of sports sciences*, *36*(15):1776-1783.

Fuller, C.W., Taylor, A., Kemp, S.P. & Raftery, M., 2017. Rugby world cup 2015: world rugby injury surveillance study. *British Journal of Sports Medicine*, *51*(1):51-57.

Garcia, M. C., & Vieira, T. M. M., 2011. Surface electromyography: Why, when, and how to use it. *Revista andaluza de medicina del deporte*, *4*(1):17-28.

Ghai, S., Driller, M., & Ghai, I. 2017. Effects of joint stabilizers on proprioception and stability: a systematic review and meta-analysis. *Physical Therapy in Sport*, *25*:65-75.

Gibson, A.L., Wagner, D. & Heyward, V., 2018. *Advanced Fitness Assessment and Exercise Prescription, 8E*. Human kinetics.

Giggins, O.M., Persson, U.M. & Caulfield, B., 2013. Biofeedback in rehabilitation. *Journal of neuroengineering and rehabilitation*, *10*(1):60.

Gokeler, A., Neuhaus, D., Benjaminse, A., Grooms, D. R., & Baumeister, J., 2019. Principles of motor learning to support neuroplasticity after ACL injury: implications for optimizing performance and reducing risk of second ACL injury. *Sports medicine*, *49*(6):853-865.

Goto, S., Aminaka, N. & Gribble, P.A., 2018. Lower-Extremity Muscle Activity, Kinematics, and Dynamic Postural Control in Individuals with Patellofemoral Pain. *Journal of sport rehabilitation*, *27*(6):505-512.

Goyal, T., Singla, M., & Paul, S., 2018. Anatomy of posterior cruciate ligament retained in a posterior cruciate ligament retaining total knee replacement: a cadaveric study. *SICOT-J*, *4*.

Gribble, P. A., & Hertel, J., 2003. Considerations for normalizing measures of the Star Excursion Balance Test. *Measurement in physical education and exercise science*, *7*(2):89-100.

Gribble, P.A., Hertel, J. & Plisky, P., 2012. Using the Star Excursion Balance Test to assess dynamic postural-control deficits and outcomes in lower extremity injury: a literature and systematic review. *Journal of athletic training*, *47*(3):339-357.

Grindem, H., Snyder-Mackler, L., Moksnes, H., Engebretsen, L. & Risberg, M.A., 2016. Simple decision rules can reduce reinjury risk by 84% after ACL reconstruction: the Delaware-Oslo ACL cohort study. *British journal of sports medicine*, *50*(13):804-808.

Grooms, D., Appelbaum, G. & Onate, J., 2015. Neuroplasticity following anterior cruciate ligament injury: a framework for visual-motor training approaches in rehabilitation. *journal of orthopaedic & sports physical therapy*, *45*(5):381-393.

Han, J., Adams, R., Waddington, G., & Anson, J. 2013. Ability to discriminate movements at multiple joints around the body: global or site-specific. *Perceptual and motor skills*, *116*(1):59-68.

Han, J., Anson, J., Waddington, G., & Adams, R. 2013. Proprioceptive performance of bilateral upper and lower limb joints: side-general and site-specific effects. *Experimental brain research*, *226*(3):313-323.

Han, J., Anson, J., Waddington, G., & Adams, R. 2014. Sport attainment and proprioception. *International Journal of Sports Science & Coaching*, *9*(1):159-170.

Han, J., Anson, J., Waddington, G., Adams, R., & Liu, Y. 2015. The role of ankle proprioception for balance control in relation to sports performance and injury. *BioMed research international*, *2015*.

Han, J., Waddington, G., Adams, R., Anson, J., & Liu, Y., 2016. Assessing proprioception: a critical review of methods. *Journal of Sport and Health Science*, *5*(1):80-90.

Hardy, A., Casabianca, L., Andrieu, K., Baverel, L., & Noailles, T., 2017. Complications following harvesting of patellar tendon or *hamstring* tendon grafts for anterior cruciate ligament reconstruction: systematic review of literature. *Orthopaedics & Traumatology: Surgery & Research*, *103*(8):245-248.

Heckmann, T.P., Noyes, F.R. & Barber-Westin, S., 2018. Rehabilitation after ACL reconstruction. *ACL Injuries in the Female Athlete*:505-535.

Herrington, L., Hatcher, J., Hatcher, A., & McNicholas, M., 2009. A comparison of Star Excursion Balance Test reach distances between ACL deficient patients and asymptomatic controls. *The Knee*, *16*(2):149-152.

Hewett TE, Zazulak BT, & Myer GD.,2007. Effects of the menstrual cycle on anterior cruciate ligament injury risk: a systematic review. *American Journal of Sports Medicine,* 35(4): 659–68.

Hind, K., Konerth, N., Entwistle, I., Theadom, A., Lewis, G., King, D., Chazot, P. & Hume, P. (2020). Cumulative Sport-Related Injuries and Longer-Term Impact in Retired Male Elite-and Amateur-Level Rugby Code Athletes and Non-contact Athletes: A Retrospective Study. *Sports Medicine*, 1-11.

Huang, P., Salmon, L., & Heath, E., 2017. ACL Rehabilitation Protocol.

Hulet, C., Sonnery-Cottet, B., Stevenson, C., Samuelsson, K., Laver, L., Zdanowicz, U., Stufkes, S., Curado, J., Verdonk, P. & Spalding, T., 2019. The use of allograft tendons in primary ACL reconstruction. *Knee Surgery, Sports Traumatology, Arthroscopy*, *27*(6):1754-1770.

Hulin, B. T., Gabbett, T. J., Lawson, D. W., Caputi, P., & Sampson, J. A., 2016. The acute: chronic workload ratio predicts injury: high chronic workload may decrease injury risk in elite rugby league players. *British journal of sports medicine*, *50*(4):231-236.

Jaco Ras, M., & Puckree, T., 2014. Injury incidence and balance in rugby players. *Pakistan journal of medical sciences*, *30*(6):1346.

Jia, Z., Xue, C., Wang, W., Liu, T., Huang, X., & Xu, W., 2017. Clinical outcomes of anterior cruciate ligament reconstruction using LARS artificial graft with an at least 7-year follow-up. *Medicine*, *96*(14).

Johnston, R. D., Gabbett, T. J., & Jenkins, D. G. 2014. Applied sport science of rugby league. *Sports medicine*, *44*(8): 1087-1100.

Joreitz, R., Lynch, A., Harner, C., Fu, F. H., & Irrgang, J. J., 2017. Criterion-Based Approach for Returning to Sport After ACL Reconstruction. In *Rotatory Knee Instability*: 397-411. Springer, Cham.

Joudeh, A. A., Alghadir, A. H., Zafar, H., Elwatidy, S. M., Tse, C., & Anwer, S., 2018. Effect of quadriceps and calf muscles fatigue on standing balance in healthy young adult males. *Journal of musculoskeletal & neuronal interactions*, *18*(2):248.

Kaeding, C.C., Léger-St-Jean, B. & Magnussen, R.A., 2017. Epidemiology and diagnosis of anterior cruciate ligament injuries. *Clinics in sports medicine*, *36*(1):1-8.

Kalra, M., Bakker, R., Tomescu, S. S., Polak, A. M., Nicholls, M., & Chandrashekar, N. 2019. The effect of unloader knee braces on medial meniscal strain. *Prosthetics and orthotics international*, *43*(2):132-139.

Kang, K. T., Koh, Y. G., Lee, J. A., & Chun, H. J. 2020. Computational biomechanics of knee joint arthroplasty: a review. *Mechanical Engineering Reviews*, *7*(1):19-00338.

Kaya, D., Calik, M., Callaghan, M. J., Yosmaoglu, B., & Doral, M. N., 2018. Proprioception After Knee Injury, Surgery and Rehabilitation. In *Proprioception in Orthopaedics, Sports Medicine and Rehabilitation*: 123-142. Springer, Cham.

Keays, S.L., Newcombe, P. & Keays, A.C., 2020. Generalized joint hypermobility in siblings with anterior cruciate ligament injuries and matched unrelated healthy siblings. *Physiotherapy Research International*, *25*(2):1826.

Kecojevic, V., Harhaji, V., & Ninković, S., 2019. Arthroscopic Anatomy of the Knee Joint and Portals. In *Meniscus of the Knee-Function, Pathology and Management*. IntechOpen.

Kemp, S.P.T., West, S., Brooks, J., Cross, M., Williams, S., Anstiss, T., Smith, A., Bryan, R., Henderson, L. & Locke, D., 2019. England Professional Rugby Injury Surveillance Project: 2017-18 Report. *Union, RF (Ed.)*.

Kempton, T., Sirotic, A. C., Rampinini, E., & Coutts, A. J., 2015. Metabolic power demands of rugby league match play. *International Journal of Sports Physiology and Performance*, *10*(1):23-28.

Khaiyat, O. A., & Norris, J., 2018. Electromyographic activity of selected trunk, core, and thigh muscles in commonly used exercises for ACL rehabilitation. *Journal of physical therapy science*, *30*(4):642-648.

Khan, T., Alvand, A., Prieto-Alhambra, D., Culliford, D. J., Judge, A., Jackson, W. F., Scammel, B.E., Arden, N.K. & Price, A. J., 2019. ACL and meniscal injuries increase the risk of primary total knee replacement for osteoarthritis: a matched case–control study using the Clinical Practice Research Datalink (CPRD). *British journal of sports medicine*, *53*(15):965-968.

King, D., Hume, P., Gissane, C., & Clark, T., 2017. Semi-professional rugby league players have higher concussion risk than professional or amateur participants: a pooled analysis. *Sports medicine*, *47*(2):197-205.

Kivlan, B. R., & Martin, R. L., 2012. Functional performance testing of the hip in athletes: a systematic review for reliability and validity. *International journal of sports physical therapy*, *7*(4): 402.

Kline, P. W., Morgan, K. D., Johnson, D. L., Ireland, M. L., & Noehren, B., 2015. Impaired quadriceps rate of torque development and knee mechanics after anterior cruciate ligament reconstruction with patellar tendon autograft. *The American journal of sports medicine*, *43*(10):2553-2558.

Koga, H., Nakamae, A., Shima, Y., Bahr, R. & Krosshaug, T. 2018. Hip and ankle kinematics in noncontact anterior cruciate ligament injury situations: video analysis using model-based image matching. *The American journal of sports medicine*, *46*(2):333-340.

Kosuge, T., Itakura, N., & Mito, K., 2013. A study for conducting waves by using the multi-channel surface EMG. In *International Conference on Digital Human Modelling and Applications in Health, Safety, Ergonomics and Risk Management* 1:223-231.

Krause, D. A., & Hollman, J. H., 2020. ELECTROMYOGRAPHIC ANALYSIS OF HIP MUSCLE ACTIVATION DURING A SINGLE LIMB SQUAT LATERAL SLIDE EXERCISE. *International Journal of Sports Physical Therapy*, *15*(5):755.

Kwon, H., Rutkove, S. B., & Sanchez, B., 2017. Recording characteristics of electrical impedance myography needle electrodes. *Physiological measurement*, *38*(9):1748.

Kwon, Y. U., & Williams III, D. B., 2017. The effect of variable rest intervals and chronic ankle instability on triplanar ankle motion during performance of the Star Excursion Balance Test. *Human movement science*, *52*:143-150.

Kyritsis, P., Bahr, R., Landreau, P., Miladi, R., & Witvrouw, E., 2016. Likelihood of ACL graft rupture: not meeting six clinical discharge criteria before return to sport is associated with a four times greater risk of rupture. *British journal of sports medicine*, *50*(15):946-951.

Laginestra, F. G., Amann, M., Kirmizi, E., Giuriato, G., Barbi, C., Ruzzante, F., ... & Venturelli, M., 2021. Electrically induced quadriceps fatigue in the contralateral leg impairs ipsilateral knee extensors performance. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology*.

Lanier, A.S., Knarr, B.A., Stergiou, N., Snyder-Mackler, L. & Buchanan, T.S. 2020. ACL injury and reconstruction affect control of ground reaction forces produced during a novel task that simulates cutting movements. *Journal of Orthopaedic Research®*.

Lanzetti, R. M., Lupariello, D., Venditto, T., Rota, P., Guzzini, M., Vadalà, A., Rota, A & Ferretti, A., 2017. The influence of playing surface on injury risk in Italian elite rugby players. *Muscles, ligaments, and tendons journal*, *7*(1):180.

Lepley, A. S., Grooms, D. R., Burland, J. P., Davi, S. M., Kinsella-Shaw, J. M., & Lepley, L. K., 2019. Quadriceps muscle function following anterior cruciate ligament reconstruction: systemic differences in neural and morphological characteristics. *Experimental brain research*, *237*(5):1267-1278.

Leppänen, M., Pasanen, K., Kujala, U.M., Vasankari, T., Kannus, P., Äyrämö, S., Krosshaug, T., Bahr, R., Avela, J., Perttunen, J. & Parkkari, J., 2017. Stiff landings are associated with increased ACL injury risk in young female basketball and floorball players. *The American journal of sports medicine*, *45*(2):386-393.

Lindsay, A., Draper, N., Lewis, J., Gieseg, S. P., & Gill, N., 2015. Positional demands of professional rugby. *European journal of sport science*, *15*(6):480-487.

Lonergan, B., Senington, B., Patterson, S.D. & Price, P., 2018. The effect of fatigue on phase specific countermovement jump asymmetries in ACL-R and non-injured rugby union players. *Translational Sports Medicine*, *1*(6):238-249.

Luo, J., Liu, C., & Yang, C., 2019. Estimation of EMG-based force using a neural-network-based approach. *IEEE Access*, *7*:64856-64865.

Lynn, S.K., Watkins, C.M., Wong, M.A., Balfany, K. & Feeney, D.F., 2018. Validity and Reliability of Surface Electromyography Measurements from a Wearable Athlete Performance System. *Journal of sports science & medicine*, *17*(2):205.

Marieswaran, M., Jain, I., Garg, B., Sharma, V., & Kalyanasundaram, D., 2018. A review on biomechanics of anterior cruciate ligament and materials for reconstruction. *Applied bionics and biomechanics*.

Martinez-Valdes, E., Falla, D., Negro, F., Mayer, F., & Farina, D. 2017. Differential motor unit changes after endurance or high-intensity interval training. *Medicine & Science in Sports & Exercise*, *49*(6): 1126-1136.

Matthews, M. J., Green, D., Matthews, H., & Swanwick, E. (2017). The effects of swimming fatigue on shoulder strength, range of motion, joint control, and performance in swimmers. *Physical Therapy in Sport*, *23*, 118-122.

Matvienko, T. Y., Zavodovskyi, D. A., Nozdrenko, D. N., Mishchenko, I. V., Motuziuk, O. P., Bogutska, K. I., & Prylutskyy, Y. I. 2017. Muscle Fatigue: Factors of Development and Ways of Prevention. *International Journal of Physiology and Pathophysiology*, *8*(4).

McCann, R. S., Crossett, I. D., Terada, M., Kosik, K. B., Bolding, B. A., & Gribble, P. A., 2017. Hip strength and star excursion balance test deficits of patients with chronic ankle instability. *Journal of science and medicine in sport*, *20*(11):992-996.

Mettler, J. A., & Griffin, L. 2016. Muscular endurance training and motor unit firing patterns during fatigue. *Experimental brain research*, *234*(1): 267-276.

Mi, Y., Katkov, M., & Tsodyks, M. 2017. Synaptic correlates of working memory capacity. *Neuron*, *93*(2):323-330.

Mirzaie, G. H., Rahimi, A., Kajbafvala, M., Manshadi, F. D., Kalantari, K. K., & Saidee, A., 2019. Electromyographic activity of the hip and knee muscles during functional tasks in males with and without patellofemoral pain. *Journal of bodywork and movement therapies*, *23*(1):54-58.

Mistry, H., Metcalfe, A., Colquitt, J., Loveman, E., Smith, N. A., Royle, P., & Waugh, N., 2019. Autograft or allograft for reconstruction of anterior cruciate ligament: a health economics perspective. *Knee Surgery, Sports Traumatology, Arthroscopy*, *27*(6):1782-1790.

Moatshe, G., & Engebretsen, L. 2020. ACL Injury: Where Are We Now? Is Prevention the Key for All Sports? In *ESSKA Instructional Course Lecture Book* (1):133-138. Springer, Berlin, Heidelberg.

Mohtadi, N., Chan, D., Barber, R. & Paolucci, E.O., 2016. Reruptures, reinjuries, and revisions at a minimum 2-year follow-up: a randomized clinical trial comparing 3 graft types for ACL reconstruction. *Clinical Journal of Sport Medicine*, *26*(2):96-107.

Montalvo, A. M., Schneider, D. K., Webster, K. E., Yut, L., Galloway, M. T., Heidt, R. S., Kaeding, C.C., Kremcheck, T.E., Magnussen, R.A., Parikh, S.N. & Stanfield, D. T., 2019. Anterior cruciate ligament injury risk in sport: A systematic review and meta-analysis of injury incidence by sex and sport classification. *Journal of athletic training*, *54*(5):472-482.

Montgomery, C., Blackburn, J., Withers, D., Tierney, G., Moran, C., & Simms, C., 2018. Mechanisms of ACL injury in professional rugby union: a systematic video analysis of 36 cases. *British Journal of Sports Medicine*, *52*(15):994-1001.

Moore, I., Vicary, D., Rafferty, J., & Mathema, P., 2020. 199 Subsequent injury risk is not specific to concussion in rugby union. *British Journal of Sports Medicine*, *54*(1):83.

Munro, A. G., & Herrington, L. C., 2010. Between-session reliability of the star excursion balance test. *Physical Therapy in Sport*, *11*(4): 128-132.

Murray, M. M., Rice, K., Wright, R. J., & Spector, M., 2003. The effect of selected growth factors on human anterior cruciate ligament cell interactions with a three-dimensional collagen-GAG scaffold. *Journal of orthopaedic research*, *21*(2):238-244.

Nagelli, C.V. & Hewett, T.E., 2017. Should return to sport be delayed until 2 years after anterior cruciate ligament reconstruction? Biological and functional considerations. *Sports medicine*, *47*(2):221-232.

Navacchia, A., Ueno, R., Ford, K.R., DiCesare, C.A., Myer, G.D. & Hewett, T.E., 2019. EMG-Informed Musculoskeletal Modeling to Estimate Realistic Knee Anterior Shear Force During Drop Vertical Jump in Female Athletes. *Annals of biomedical engineering*, *47*(12):2416-2430.

Nessler, T., Denney, L. & Sampley, J., 2017. ACL injury prevention: what does research tell us? *Current reviews in musculoskeletal medicine*, *10*(3):281-288.

Nodehi-Moghadam, A., Nasrin, N., Kharazmi, A., & Eskandari, Z. 2013. A comparative study on shoulder rotational strength, range of motion and proprioception between the throwing athletes and non-athletic persons. *Asian journal of sports medicine*, *4*(1):34.

Norris, B., & Trudelle-Jackson, E., 2011. Hip-and thigh-muscle activation during the star excursion balance test. *Journal of sport rehabilitation*, *20*(4):428-441.

Nunley, R. M., Wright, D., Renner, J. B., Yu, B., & Garrett Jr, W. E., 2003. Gender comparison of patellar tendon tibial shaft angle with weight bearing. *Research in Sports Medicine*, *11*(3):173-185.

O'Connell, E., & Molloy, M. G., 2016. Concussion in rugby: knowledge and attitudes of players. *Irish Journal of Medical Science (19)*, *185*(2):521-528.

Onate, J., Herman, D., Grooms, D., Sutton, Z. & Wilkerson, G., 2019. Neuroscience Principles for ACL. *Return to Sport after ACL Reconstruction and Other Knee Operations: Limiting the Risk of Reinjury and Maximizing Athletic Performance*:359.

Ouattas, A., Wellsandt, E., Hunt, N. H., Boese, C. K., & Knarr, B. A. 2019. Comparing single and multi-joint methods to detect knee joint proprioception deficits post primary unilateral total knee arthroplasty. *Clinical Biomechanics*, *68*:197-204.

Pappas, E., Nightingale, E. J., Simic, M., Ford, K. R., Hewett, T. E., & Myer, G. D., 2015. Do exercises used in injury prevention programmes modify cutting task biomechanics? A systematic review with meta-analysis. *British journal of sports medicine*, *49*(10):673-680.

Petersen, W., & Tillmann, B. 2002 Anatomy and function of the anterior cruciate ligament. Orthopade 31(8):710-8.

Phinyomark, A., Campbell, E., & Scheme, E. 2020. Surface electromyography (EMG) signal processing, classification, and practical considerations. In *Biomedical signal processing,* 3-29. Springer, Singapore.

Plisky, P. J., Rauh, M. J., Kaminski, T. W., & Underwood, F. B., 2006. Star Excursion Balance Test as a predictor of lower extremity injury in high school basketball players. *Journal of orthopaedic & sports physical therapy*, *36*(12):911-919.

Price, M. J., Tuca, M., Cordasco, F. A., & Green, D. W., 2017. Nonmodifiable risk factors for anterior cruciate ligament injury. *Current opinion in paediatrics*, *29*(1):55-64.

Proske, U., & Gandevia, S. C., 2012. The proprioceptive senses: their roles in signalling body shape, body position and movement, and muscle force. *Physiological reviews*.

Quarrie, K. L., Hopkins, W. G., Anthony, M. J., & Gill, N. D., 2013. Positional demands of international rugby union: evaluation of player actions and movements. *Journal of Science and Medicine in Sport*, *16*(4):353-359.

Rahnemai-Azar, A. A., Abebe, E. S., Johnson, P., Labrum, J., Fu, F. H., Irrgang, J. J., Sameulsson, K., & Musahl, V. 2017. Increased lateral tibial slope predicts high-grade rotatory knee laxity pre-operatively in ACL reconstruction. *Knee Surgery, Sports Traumatology, Arthroscopy*, *25*(4):1170-1176.

Rajagopal, A., Dembia, C.L., DeMers, M.S., Delp, D.D., Hicks, J.L. & Delp, S.L., 2016. Full-body musculoskeletal model for muscle-driven simulation of human gait. *IEEE transactions on biomedical engineering*, *63*(10):2068-2079.

Rashedi, E., & Nussbaum, M. A. 2017. Quantifying the history dependency of muscle recovery from a fatiguing intermittent task. *Journal of biomechanics*, *51*: 26-31.

Raymond, J., & Hiller, C. 2019. The Effect of a 4-Week Wobble Board Training Program on Proprioceptive Acuity. *Critical Reviews™ in Physical and Rehabilitation Medicine*, *31*(4).

Rodacki, A. L., Fowler, N. E., & Bennett, S. J., 2002. Vertical jump coordination: fatigue effects. *Medicine Science Sports Exercise*, *34*(1):105-116.

Roe, M., Murphy, J.C., Gissane, C. & Blake, C., 2018. *Hamstring* injuries in elite Gaelic football: an 8-year investigation to identify injury rates, time-loss patterns, and players at increased risk. *British journal of sports medicine*, *52*(15):982-988.

Roldán Jiménez, C., Bennett, P., Ortiz Garcia, A., & Cuesta Vargas, A. I., 2019. Fatigue detection during sit-to-stand test based on surface electromyography and acceleration: a case study. *Sensors*, *19*(19):4202.

Romero-Franco, N., Martínez-López, E. J., Hita-Contreras, F., Lomas-Vega, R., & Martínez-Amat, A. 2014. Short-term effects of anaerobic lactic exercise on knee proprioception of track and field athletes. *Isokinetics and Exercise Science*, *22*(3): 205-210.

Sahin, E., Dilek, B., Baydar, M., Gundogdu, M., Ergin, B., Manisali, M., Akalin, E., & Gulbahar, S. 2017. Shoulder proprioception in patients with subacromial impingement syndrome. *Journal of back and musculoskeletal rehabilitation*, *30*(4):857-862.

Saltzman, B. M., Cvetanovich, G. L., Nwachukwu, B. U., Mall, N. A., Bush-Joseph, C. A., & Bach Jr, B. R., 2016. Economic analyses in anterior cruciate ligament reconstruction: a qualitative and systematic review. *The American journal of sports medicine*, *44*(5):1329-1335.

Samuelsen, B. T., Webster, K. E., Johnson, N. R., Hewett, T. E., & Krych, A. J., 2017. *Hamstring* autograft versus patellar tendon autograft for ACL reconstruction: is there a difference in graft failure rate? A meta-analysis of 47,613 patients. *Clinical Orthopaedics and Related Research®*, *475*(10):2459-2468.

Sánchez-Sánchez, J., Gallardo-Guerrero, A. M., García-Gallart, A., Sánchez-Sáez, J. A., Felipe, J. L., & Encarnación-Martínez, A., 2019. Influence of the structural components of artificial turf systems on impact attenuation in amateur football players. *Scientific reports*, *9*(1):1-9.

Sarabon, N., Panjan, A., Rosker, J., & Fonda, B. 2013. Functional and neuromuscular changes in the *hamstring*s after drop jumps and leg curls. *Journal of sports science & medicine*, *12*(3):431.

Sarah, J. & Oh, R., 2016. Successful Injury Prevention Interventions. In *Musculoskeletal Injuries in the Military*. Springer, New York, NY.

Sarmento, H., Anguera, M. T., Pereira, A., & Araújo, D. 2018. Talent identification and development in male football: a systematic review. *Sports Medicine*, *48*(4):907-931.

Schorderet, C., Allet, L., & Hilfiker, R., 2020. The role of the dominant leg while assessing balance performance. A systematic review and meta-analysis. *Gait & posture*.

Schreurs, M. J., Benjaminse, A., & Lemmink, K. A., 2017. The effect of cutting angle on knee mechanics in invasion sport athletes. *Journal of biomechanics*, *63*:144-150.

Schutte, M. J., Dabezies, E. J., Zimny, M. L., & Happel, L. T., 1987. Neural anatomy of the human anterior cruciate ligament. *The Journal of bone and joint surgery. American volume*, *69*(2):243-247.

Segal, N.A., Nevitt, M.C., Welborn, R.D., Nguyen, U.S., Niu, J., Lewis, C.E., Felson, D.T., Frey-Law, L. & Group, M.I., 2015. The association between antagonist *hamstring* coactivation and episodes of knee joint shifting and buckling. *Osteoarthritis and cartilage*, *23*(7):1112-1121.

Sell, T. C., & Lephart, S. M. 2018. Neuromuscular differences between men and women. In *ACL Injuries in the Female Athlete* (1):133-152. Springer, Berlin, Heidelberg.

Seminati, E., Cazzola, D., Preatoni, E., & Trewartha, G. (2017). Specific tackling situations affect the biomechanical demands experienced by rugby union players. *Sports Biomechanics*, *16*(1), 58-75.

Sewry, N., Verhagen, E., Lambert, M., Van Mechelen, W., Marsh, J., Readhead, C., Viljoen, W. & Brown, J., 2018. Trends in time-loss injuries during the 2011-2016 South African Rugby Youth Weeks. *Scandinavian journal of medicine & science in sports*, *28*(9):2066-2073.

Sharma, R. 2017. Effect of Fatigue on the Proprioception Acuity of Quadriceps Muscle after Inducing Fatigue and Followed by Local Cooling in the Same Muscle. *Journal of Exercise Science & Physiotherapy*, *13*(2).

Sherrington, C. S. 1906. 1947 The Integrative Action of the Nervous System. (7).

Shukla, M., Bindal, V. D., & Pandey, V., 2019. Systematic review of recovery protocols for athletes following ACL injuries: Surgical vs. conservative treatment. *Physiotherapy-The Journal of Indian Association of Physiotherapists*, *13*(2):58.

Silvers-Granelli, H.J., Bizzini, M., Arundale, A., Mandelbaum, B.R. & Snyder-Mackler, L., 2017. Does the FIFA 11+ injury prevention program reduce the incidence of ACL injury in male soccer players? *Clinical Orthopaedics and Related Research®*, *475*(10):2447-2455.

Sim, J., Saunders, B., Waterfield, J. & Kingstone, T., 2018. Can sample size in qualitative research be determined a priority? *International Journal of Social Research Methodology*, *21*(5):619-634.

Smale, K. B., Alkjaer, T., Flaxman, T. E., Krogsgaard, M. R., Simonsen, E. B., & Benoit, D. L., 2019. Assessment of objective dynamic knee joint control in anterior cruciate ligament deficient and reconstructed individuals. *The Knee*, *26*(3):578-585.

Smeets, A., Vanrenterghem, J. O. S., Staes, F., Vandenneucker, H., Claes, S., & Verschueren, S., 2020. Are ACL reconstructed athletes more vulnerable to fatigue than uninjured athletes. *Medicine and science in sports and exercise*, *52*(2):345-353.

Smith, D. R., King, R. F. G. J., Duckworth, L. C., Sutton, L., Preston, T., O'Hara, J. P., & Jones, B., 2018. Energy expenditure of rugby players during a 14-day in-season period, measured using doubly labelled water. *European journal of applied physiology*, *118*(3):647-656.

Smith, S., 2019. Testing the Validity and Reliability of Electromyography Acquisition Capabilities of a Wearable EMG Device, Sense3, by Strive.

Staiano, W., Bosio, A., de Morree, H. M., Rampinini, E., & Marcora, S. 2018. The cardinal exercise stopper: Muscle fatigue, muscle pain or perception of effort? In *Progress in brain research*, 240:175-200.

Stanley, L. E., Harkey, M., Luc-Harkey, B., Frank, B. S., Pietrosimone, B., Blackburn, J. T., & Padua, D. A., 2019. Ankle Dorsiflexion displacement is associated with hip and knee kinematics in females following anterior cruciate ligament reconstruction. *Research in Sports Medicine*, *27*(1):21-33.

Starling, L. T., 2019. Teams with lower injury rates have greater success in the Currie Cup rugby union competition. *South African Journal of Sports Medicine*, *31*(1):1-2.

Starling, L., Readhead, C., Viljoen, W., & Lambert, M., 2020. The Currie Cup Premiership Competition Injury Surveillance Report 2019. *South African Journal of Sports Medicine*, *32*(1).

Stiffler, M. R., Bell, D. R., Sanfilippo, J. L., Hetzel, S. J., Pickett, K. A., & Heiderscheit, B. C., 2017. Star excursion balance test anterior asymmetry is associated with injury status in division I collegiate athletes. *Journal of orthopaedic & sports physical therapy*, *47*(5):339-346.

Suen, L. J. W., Huang, H. M., & Lee, H. H., 2014. A comparison of convenience sampling and purposive sampling. *Hu Li Za Zhi*, *61*(3):105.

Sugimoto, D., Myer, G. D., McKeon, J. M., & Hewett, T. E., 2012. Evaluation of the effectiveness of neuromuscular training to reduce anterior cruciate ligament injury in female athletes: a critical review of relative risk reduction and numbers-needed-to-treat analyses. *British journal of sports medicine*, *46*(14):979-988.

Sun, D., Gu, Y., Mei, Q., & Baker, J. S., 2017. Different soccer stud configurations effect on running and cutting movements. *International Journal of Biomedical Engineering and Technology*, *24*(1):19-32.

Takahashi, S., Nagano, Y., Ito, W., Kido, Y. & Okuwaki, T., 2019. A retrospective study of mechanisms of anterior cruciate ligament injuries in high school basketball, handball, judo, soccer, and volleyball. *Medicine*, *98*(26):235.

Takazawa, Yuji, Masataka Nagayama, Hiroshi Ikeda, Takayuki Kawasaki, Muneaki Ishijima, Yoshitomo Saita, Haruka Kaneko, Yohei Kobayashi, Shinnosuke Hada, and Kazuo Kaneko., 2016 "Anterior cruciate ligament injuries in elite and high school rugby players: a 11-year review." *The Physician and Sportsmedicine* 44, no. 1:53-58.

Talarico, M.K., Lynall, R.C., Mauntel, T.C., Weinhold, P.S., Padua, D.A. & Mihalik, J.P., 2017. Static and dynamic single leg postural control performance during dual-task paradigms. *Journal of sports sciences*, *35*(11):1118-1124.

Tee, J. C., Klingbiel, J. F., Collins, R., Lambert, M. I., & Coopoo, Y., 2016. Preseason Functional Movement Screen component tests predict severe contact injuries in professional rugby union players. *Journal of strength and conditioning research*, *30*(11):3194-3203.

Thomas, K., Dent, J., Howatson, G. & Goodall, S., 2017. Etiology and recovery of neuromuscular fatigue after simulated soccer match play. *Medicine & Science in Sports & Exercise*, 49(5):955-964.

Thompson, S. M., Salmon, L. J., Waller, A., Linklater, J., Roe, J. P., & Pinczewski, L. A., 2016. Twenty-year outcome of a longitudinal prospective evaluation of isolated endoscopic anterior cruciate ligament reconstruction with patellar tendon or *hamstring* autograft. *The American journal of sports medicine*, *44*(12):3083-3094.

Till, K., Cobley, S., Morley, D., O'hara, J., Chapman, C., & Cooke, C. (2016). The influence of age, playing position, anthropometry, and fitness on career attainment outcomes in rugby league. *Journal of sports sciences*, *34*(13), 1240-1245.

Tomescu, S., Bakker, R., Wasserstein, D., Kalra, M., Nicholls, M., Whyne, C., & Chandrashekar, N., 2018. Dynamically tensioned ACL functional knee braces reduce ACL and meniscal strain. *Knee Surgery, Sports Traumatology, Arthroscopy*, *26*(2):526-533.

Tuthill, J. C., & Azim, E., 2018. Proprioception. *Current Biology*, *28*(5): R194-R203.

Vafadar, A. K., Côté, J. N., & Archambault, P. S., 2016. Interrater and intrarater reliability and validity of 3 measurement methods for shoulder-position sense. *Journal of sport rehabilitation*, *25*(1).

van Melick, N., van Cingel, R. E., Brooijmans, F., Neeter, C., van Tienen, T., Hullegie, W., & Nijhuis-van der Sanden, M. W., 2016. Evidence-based clinical practice update: practice guidelines for anterior cruciate ligament rehabilitation based on a systematic review and multidisciplinary consensus. *British journal of sports medicine*, *50*(24):1506-1515.

Vaulerin, J., Chorin, F., Emile, M., d'Arripe-Longueville, F., & Colson, S. S., 2019. Ankle Sprains' Risk Factors in a Sample of French Firefighters: A Preliminary Prospective Study. *Journal of sport rehabilitation*, *1*(2):1-8.

Vaz, L. M. T., Gonçalves, B. S. V., Figueira, B. E. N., & Garcia, G. C., 2016. Influence of different small-sided games on physical and physiological demands in rugby union players. *International Journal of Sports Science & Coaching*, *11*(1):78-84.

Vitak, J., Shilton, K., & Ashktorab, Z., 2016. Beyond the Belmont principles: Ethical challenges, practices, and beliefs in the online data research community. In *Proceedings of the 19th ACM Conference on Computer-Supported Cooperative Work & Social Computing*,1(1): 941-953.

Viviers, P. L., Viljoen, J. T., & Derman, W., 2018. A review of a decade of rugby Union injury epidemiology: 2007-2017. *Sports Health*, *10*(3):223-227.

Volpi, P., Bisciotti, G.N., Chamari, K., Cena, E., Carimati, G. & Bragazzi, N.L., 2016. Risk factors of anterior cruciate ligament injury in football players: a systematic review of the literature. *Muscles, ligaments, and tendons journal*, *6*(4):480.

Walsh, G. S., 2017. Effect of static and dynamic muscle stretching as part of warm up procedures on knee joint proprioception and strength. *Human movement science*, *55*:189-195.

Wang, H.J., Ao, Y.F., Chen, L.X., Xi, G.O.N.G., Wang, Y.J., Yong, M.A., Leung, K.K.M. & YU, J.K., 2011. Second-look arthroscopic evaluation of the articular cartilage after primary single-bundle and double-bundle anterior cruciate ligament reconstructions. *Chinese medical journal*, *124*(21):3551-3555.

Wasserstein, D., Sheth, U., Cabrera, A., & Spindler, K. P., 2015. A systematic review of failed anterior cruciate ligament reconstruction with autograft compared with allograft in young patients. *Sports health*, *7*(3):207-216.

Webster, K. A., Pietrosimone, B. G., & Gribble, P. A., 2016. Muscle activation during landing before and after fatigue in individuals with or without chronic ankle instability. *Journal of athletic training*, *51*(8):629-636.

Wellsandt, E., Failla, M. J., Axe, M. J., & Snyder-Mackler, L., 2018. Does anterior cruciate ligament reconstruction improve functional and radiographic outcomes over nonoperative management 5 years after injury? *The American journal of sports medicine*, *46*(9):2103-2112.

West, S., 2018. England professional rugby injury report. 2017/8 Season. *Rugby Football. Union*:1-60.

Wetters, N., Weber, A.E., Wuerz, T.H., Schub, D.L. & Mandelbaum, B.R., 2016. Mechanism of injury and risk factors for anterior cruciate ligament injury. *Operative Techniques in Sports Medicine*, *24*(1):2-6.

Wiggins, A.J., Grandhi, R.K., Schneider, D.K., Stanfield, D., Webster, K.E. & Myer, G.D., 2016. Risk of secondary injury in younger athletes after anterior cruciate ligament reconstruction: a systematic review and meta-analysis. *The American journal of sports medicine*, *44*(7):1861-1876.

Wild, C. Y., Grealish, A., & Hopper, D., 2017. Lower limb and trunk biomechanics after fatigue in competitive female Irish dancers. *Journal of athletic training*, *52*(7):643-648.

Williams S, Trewartha G, Kemp S, & Stokes K. 2013. A meta-analysis of injuries in senior men’s professional rugby union. *Sports Med.* 43(10):1043–55.

Williams, S., Trewartha, G., Kemp, S.P., Brooks, J.H., Fuller, C.W., Taylor, A.E., Cross, M.J. & Stokes, K.A., 2016. Time loss injuries compromise team success in Elite Rugby Union: a 7-year prospective study. *British journal of sports medicine*, *50*(11):651-656.

Windt, J., & Gabbett, T. J., 2017. How do training and competition workloads relate to injury? The workload—injury aetiology model. *British Journal of Sports Medicine*, *51*(5):428-435.

World rugby. 2020. Men’s world rugby rankings. [Online]. Available at: https://www.world.rugby/rankings/mru?lang=en. Accessed on 2 May 2020.

Xerri, C. 2012. Plasticity of cortical maps: multiple triggers for adaptive reorganization following brain damage and spinal cord injury. *The Neuroscientist*, *18*(2):133-148.

Xie, X., Liu, X., Chen, Z., Yu, Y., Peng, S., & Li, Q., 2015. A meta-analysis of bone–patellar tendon–bone autograft versus four-strand *hamstring* tendon autograft for anterior cruciate ligament reconstruction. *The Knee*, *22*(2):100-110.

Yang, B. I., & Ma, S. R. 2018. Effects of quadriceps muscle fatigue on balance with subacute stroke. *International Journal of Pure and Applied Mathematics*, *118*(19): 1145-1155.

Yeomans, C., Kenny, I. C., Cahalan, R., Warrington, G. D., Harrison, A. J., Hayes, K., & Comyns, T. M. 2018. The incidence of injury in amateur male rugby union: a systematic review and meta-analysis. *Sports medicine*, *48*(4):837-848.

Yoo, S. H., Song, E. K., Shin, Y. R., Kim, S. K., & Seon, J. K., 2017. Comparison of clinical outcomes and second-look arthroscopic findings after ACL reconstruction using a *hamstring* autograft or a tibialis allograft. *Knee Surgery, Sports Traumatology, Arthroscopy*, *25*(4):1290-1297.

You, C. K., Chou, C. L., Wu, W. T., & Hsu, Y. C., 2019. Nonoperative choice of anterior cruciate ligament partial tear: ultrasound-guided platelet-rich plasma injection. *Journal of medical ultrasound*, *27*(3):148.

Zaylor, W., Stulberg, B.N. & Halloran, J.P., 2019. Use of distraction loading to estimate subject-specific knee ligament slack lengths. *Journal of biomechanics*, *92*:1-5.

Zebis, M.K., Andersen, C.H., Bencke, J., Ørntoft, C., Linnebjerg, C., Hölmich, P., Thorborg, K., Aagaard, P. & Andersen, L.L., 2017. Neuromuscular coordination deficit persists 12 months after ACL reconstruction but can be modulated by 6 weeks of kettlebell training: a case study in women’s elite soccer. *Case reports in orthopaedics*, *2017*.

Zeng, C., Gao, S. G., Li, H., Yang, T., Luo, W., Li, Y. S., & Lei, G. H., 2016. Autograft versus allograft in anterior cruciate ligament reconstruction: a meta-analysis of randomized controlled trials and systematic review of overlapping systematic reviews. *Arthroscopy: The Journal of Arthroscopic & Related Surgery*, *32*(1):153-163.

Zhang, L., Hacke, J. D., Garrett, W. E., Liu, H., & Yu, B., 2019. Bone bruises associated with anterior cruciate ligament injury as indicators of injury mechanism: a systematic review. *Sports Medicine*, *49*(3):453-462.

Zulfikri, N., & Justine, M., 2017. Effects of kinesio® taping on dynamic balance following fatigue: A randomized controlled trial. *Physical therapy research*, *20*(1):16-22.

APPENDIX A – WARM UP PROTOCOL

The importance of warm up procedures prior to athletic performance is well recognized. Dynamic stretching should be favoured over static stretching as dynamic stretching improves knee joint position sense (Wals, 2017:189). The following dynamic exercises have been chosen by the researcher:

5 minutes on bike ergometer or treadmill	
High knees	30 sec
Butt kicks	30 sec
A – Skips	30 sec
Monster walks	8 steps to each side
Body weight squats	8 repetitions
Alternating forward lunges	8 steps with both sides

The participant will be asked whether he feels warmed up, if yes participant will move straight into the MVC with the EMG.

High knees: Lift alternating knees as high as possible at a high pace for 30 seconds.

Butt kicks: Bring foot under leg until heel touches buttocks while performing a medium paced jog.

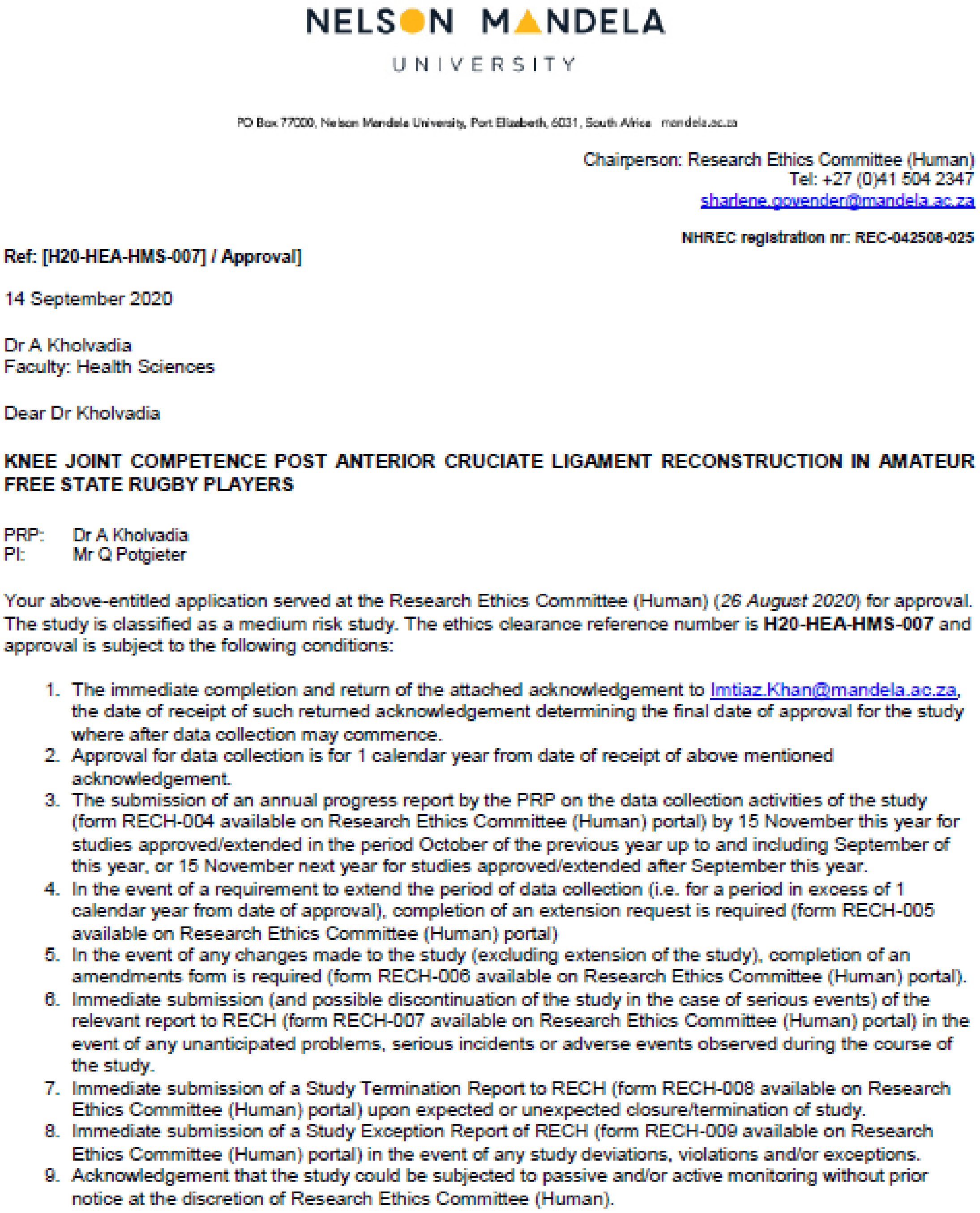
A – Skips: Lift knee up with double touch of opposite foot before alternating legs. This should be done at a fast pace.

Monster walks: Go into squat position, knees bent and back straight, walk to the side without coming back up with body.

Body weight squats: Feet shoulder width apart, bend knees while keeping spine straight and knees above toes.

Alternating forward lunges: With hands on hips, take a big step forward, lunge downward until knee almost touches ground the come back up and alternate legs.

APPENDIX B – ETHICAL CLEARANCE



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NHREC registration nr: REC-042508-025

Ref: [H20-HEA-HMS-007] / Approval]

14 September 2020

Dr A Kholvadia
Faculty: Health Sciences

Dear Dr Kholvadia

KNEE JOINT COMPETENCE POST ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION IN AMATEUR FREE STATE RUGBY PLAYERS

PRP: Dr A Kholvadia
PI: Mr Q Potgieter

Your above-entitled application served at the Research Ethics Committee (Human) (*26 August 2020*) for approval. The study is classified as a medium risk study. The ethics clearance reference number is **H20-HEA-HMS-007** and approval is subject to the following conditions:

1. The immediate completion and return of the attached acknowledgement to Imtiaz.Khan@mandela.ac.za, the date of receipt of such returned acknowledgement determining the final date of approval for the study where after data collection may commence.
2. Approval for data collection is for 1 calendar year from date of receipt of above mentioned acknowledgement.
3. The submission of an annual progress report by the PRP on the data collection activities of the study (form RECH-004 available on Research Ethics Committee (Human) portal) by 15 November this year for studies approved/extended in the period October of the previous year up to and including September of this year, or 15 November next year for studies approved/extended after September this year.
4. In the event of a requirement to extend the period of data collection (i.e. for a period in excess of 1 calendar year from date of approval), completion of an extension request is required (form RECH-005 available on Research Ethics Committee (Human) portal)
5. In the event of any changes made to the study (excluding extension of the study), completion of an amendments form is required (form RECH-006 available on Research Ethics Committee (Human) portal).
6. Immediate submission (and possible discontinuation of the study in the case of serious events) of the relevant report to RECH (form RECH-007 available on Research Ethics Committee (Human) portal) in the event of any unanticipated problems, serious incidents or adverse events observed during the course of the study.
7. Immediate submission of a Study Termination Report to RECH (form RECH-008 available on Research Ethics Committee (Human) portal) upon expected or unexpected closure/termination of study.
8. Immediate submission of a Study Exception Report of RECH (form RECH-009 available on Research Ethics Committee (Human) portal) in the event of any study deviations, violations and/or exceptions.
9. Acknowledgement that the study could be subjected to passive and/or active monitoring without prior notice at the discretion of Research Ethics Committee (Human).

Please quote the ethics clearance reference number in all correspondence and enquiries related to the study. For speedy processing of email queries (to be directed to Imtiaz.Khan@mandela.ac.za), it is recommended that the ethics clearance reference number together with an indication of the query appear in the subject line of the email.

We wish you well with the study.

Yours sincerely

Govender

Dr S Govender
Chairperson: Research Ethics Committee (Human)

Cc: Department of Research Development
Faculty Manager: Health Sciences

Appendix 1: Acknowledgement of conditions for ethical approval

APPENDIX C – RESULT SHEET

NELSON MANDELA UNIVERSITY	KNEE COMPETENCE POST ACL RECONSTRUCTION IN SWD RUGBY PLAYERS
	Masters study - Biokinetics by QC Potgieter

Height:		**Blood pressure:**	
Weight:		**BMI:**	

COMMENTS:

LENGTHS

	Left		Right
Ankle width:		mm	
knee width:		mm	
Leg length functional:		mm	
Leg length anatomical:		mm	
Femur Length:		mm	
Tibial Length:		mm	

CIRCUMFERENCES

Waist Circumference:		cm	
Hip Circumference:		cm	
5cm above knee joint line:		cm	
Knee joint line:		cm	
5cm below knee joint line:		cm	

FLEXIBILITY

Knee flexion (active)		degrees	
Knee flexion (passive)		degrees	
Knee Extension		degrees	
SLR (active)		degrees	
SLR (passive)		degrees	

STAR EXCURSION TEST	LNF	LF	RNF	RF
1 Anterolateral				
2 Anterior				
3 Anteromedial				
4 Medial				
5 Posteromedial				
6 Posterior				
7 Posterolateral				
8 Lateral				

APPENDIX D – INFORMED CONSENT FORM

RESEARCHER'S DETAILS	
Title of the research project	**Knee Joint Competence Post ACL Reconstruction In amateur South Western District Rugby Players**
Reference number	
Principal investigator(s)	**Quinten Potgieter, Aayesha Kholvadia, Lee Pote**
Address	**Nelson Mandela University (South Campus) Building 125 0122**
Postal Code	**6025**
Contact telephone number (private numbers not advisable)	**Tel: 082 872 6352** **Email: s214041824@mandela.ac.za**

A. DECLARATION BY OR ON BEHALF OF PARTICIPANT		Initial
I, the participant, and the undersigned	(Full names)	
ID number		
OR		
I, in my capacity as	(Parent or guardian)	
of the participant	(Full names)	
ID number		
Address (of participant)		

A.1 HEREBY CONFIRM AS FOLLOWS:		Initial
I, the participant, was invited to participate in the above-mentioned research project		
that is being undertaken by	Quinten Potgieter	
From	The Department of Human Movement Science, Faculty of Health Science	
of the Nelson Mandela University.		

THE FOLLOWING ASPECTS HAVE BEEN EXPLAINED TO ME, THE PARTICIPANT:					Initial
2.1	**Aim:**	The aim of this study is to identify knee joint competence post ACLR in amateur SWD rugby players between the involved and uninvolved sides.			
2.2	**Procedures:**	The participant will do two Star Excursion Balance Tests (SEBT) on both legs with a fatigue protocol to be met before the start of the second SEBT. Participant will start with the uninvolved side and finish both SEBT and fatigue protocol before moving onto the involved side. This test takes up to 45 minutes to complete.			
2.3	**Risks:**	Any participant screened that may have a chance for re-injury will be eliminated. Participants may experience the delayed onset of muscle soreness (DOMS).			
2.4	**Possible benefits:**	The researcher will be able to identify if the player has any increased risks of ACL reinjury when combining the results of both the SEBT and muscle activation tests. It will provide us with the ability to have a baseline result for the player should he succumb to an injury during the season. This will aid in the clearance test for return to sport post injury.			
2.5	**Confidentiality:**	Participant identity will not be revealed in any discussion, description or scientific publications by the investigators will make use of number assignments, randomly allocated to protect confidentiality.			
2.6	**Access to findings:**	Any new information or benefit that develops during the course of the study will be shared verbally and in writing to me as an individual as well as to coaches and stakeholders involved in the research process.			
2.6	**Voluntary participation / refusal / discontinuation:**	My participation is voluntary	YES		
		My decision whether or not to participate will in no way affect my present or future care / employment / lifestyle	TRUE		

3. THE INFORMATION ABOVE WAS EXPLAINED TO ME/THE PARTICIPANT BY:									Initial
Quinten Potgieter									
in	**Afrikaans**		**English**		**Xhosa**		**Other**		
and I am in command of this language, **or** it was satisfactorily translated to me by									
(Not applicable)									
I was given the opportunity to ask questions and all these questions were answered satisfactorily.									

4.	No pressure was exerted on me to consent to participation, and I understand that I may withdraw at any stage without penalisation.	
5.	Participation in this study will not result in any additional cost to myself.	

A.2 I HEREBY VOLUNTARILY CONSENT TO PARTICIPATE IN THE ABOVE-MENTIONED PROJECT:

Signed/confirmed at	on	20
	Signature of witness:	
Signature or right thumb print of participant	Full name of witness:	

STATEMENT BY OR ON BEHALF OF INVESTIGATOR(S)

I,	Quinten Potgieter	declare that:							
1.	I have explained the information given in this document to								
	and / or his representative								
2.	He was encouraged and given ample time to ask me any questions;								
3.	This conversation was conducted in	**Afrikaans**		**English**	x	**Xhosa**		**Other**	
	And no translator was used, OR this conversation was translated into								
	(language)	by	(Not applicable)						
4.	I have detached Section D and handed it to the participant	YES	NO						
Signed/confirmed at		on	20						
Signature of interviewer	Signature of witness:								
	Full name of witness:								

APPENDIX E – STUDY OUTLINE

NELSON MANDELA
UNIVERSITY
PO BOX: 7700
Nelson Mandela University
Port Elizabeth◦ 6031
South Africa
www.mandela.ac.za

KNEE JOINT COMPETENCE POST ACL RECONSTRUCTION IN AMATEUR SOUTH WESTERN DISTRICT RUGBY PLAYERS.

Good day, I, Quinten Potgieter am currently doing my M(HMS) (Research) in Biokinetics with research focused on amateur rugby players in the SWD. This study will be performed under the supervision of Dr A Kholvadia from the Nelson Mandela University. In this study we want to establish whether there is a relationship between knee joint muscle activation and proprioception qualities after neuromuscular fatigue. We also want to identify whether the anterior cruciate ligament (ACL) reconstructed side potentially lacks proprioception or has a significant muscle activation difference from the uninjured side correlates with a bigger risk of reinjury rate.

We invite you as an amateur rugby player between the ages of 19yrs-32yrs to partake in this research study.

Inclusion criteria:

- SWD club male rugby player affiliated with SARU.
- Amateur player, turning 19 (in 2020) – 32 years old.
- Involved in any form of moderate intensity exercise four days per week, due to Covid-19 rugby specific training has been suspended in South Africa rugby.
- Within 3 years post ACL injury with clearance from rehabilitation specialist to return to play.

The player will be asked to complete his personal details and injury screening questionnaire. To be included in the study, the player will have to sign a consent form giving the researcher permission to add his results to the study. All collected data will be kept confidential and no identifying information will be included in the final write up of the study. Only the researcher, and the two supervisors will have access to the raw data. Once the documentation has been completed and anthropometrical data has been collected, the prospective participant will be requested to perform two sets of the Star Excursion Balance Tests (SEBT) on both legs with a fatigue protocol to be met before the start of the second SEBT. The estimated time is 45 minutes per participant.

There is potential risk to participation in this study. The benefits of participating in this study include but are not exclusive to; risk identification for ACL re-injury, baseline data which could serve as a clearance test for return to post injury play. Upon completion the participant will be provided with the results obtained from the testing.

Data collection and testing will take place at Potgieter, and Pike Biokineticists located in George.

Participation is voluntary and refusal to participate will involve no penalty or loss of benefits to which the participant is otherwise entitled. The prospective participant may also discontinue participation at any time without penalty or loss of benefits to which the participant is otherwise entitled.

For standardisation of data collection, the following participants will be excluded from this study; players who may have current lower limb injuries using medical clearance from team physician. Any player that presents with a medical condition, identified by the Personal Information and injury screening, that has the potential to be aggravated by the testing performed during NMF protocol or SEBT.

Should you require any additional information regarding this study feel free to contact me or the study supervisor, Dr A Kholvadia (Aayesha.kholvadia@mandela.ac.za).

Thank you in advance for your co-operation.

Quinten Potgieter (master’s student) Nelson Mandela University
Human Movement Sciences Department
Summerstrand Campus (South)
Building 125
Port Elizabeth 6031, South Africa
Email: s214041824@mandela.ac.za

APPENDIX F – MEDICAL QUESTIONNAIRE

PHYSICAL ACTIVITY SCREENING QUESTIONNAIRE

Name: ___________________________

Rugby Club: ___________________________

MEDICAL HISTORY

Tick any of the following conditions, diseases, or disorders that you have had in the past or are presently being treated for by a physician or health professional.

☐ Heart problems
☐ Peripheral vascular disorders
☐ High/low blood pressure
☐ Epilepsy
☐ Anaemia
☐ Asthma
☐ Emphysema
☐ Migraine
☐ Eye problems
☐ Hypoglycaemia
☐ Diabetes
☐ Hyperthyroidism

☐ Other (specify): ____

Have you had any recent medical problems? If so, give details below:

____

____

Are you currently suffering from any orthopaedic disorder problem? If so, briefly describe the problem:

____

____

Are there any other concerns, medical or otherwise, that you feel are worth mentioning?

____

____

Please indicate any prescribed or over the counter medication that you are currently taking or have taken in the past 6 months:

____

____

Have you had anterior cruciate ligament (ACL) reconstruction in the last 2 years:

YES	NO

If Yes, how long ago, how did the injury occur and what graft did they use:

____

____

____

OTHER HABITS

Please tick appropriate box:

Do you smoke?

YES	NO

If yes, how many cigarettes per day: _______

EXERCISE HISTORY

Do you exercise regularly?

YES	NO

How many days per week do you normally spend performing at least 20 minutes of moderate to strenuous exercise?

1	2	3	4	5	6	7	0

Do you experience shortness of breath or chest discomfort with exercise?

YES	NO

APPENDIX G – GATE KEEPER PERMISSION

NELSON MANDELA
UNIVERSITY

PO BOX: 7700 ◦
Nelson Mandela University
Port Elizabeth◦ 6031◦
South Africa◦
www.mandela.ac.za

Date: ____________________

RE: Permission from gatekeeper

To whom it may concern:

I, ____ (full name) hereby give Quinten Potgieter permission to conduct his testing, entitled: “*Knee joint competence post anterior cruciate ligament reconstruction in amateur South Western District rugby players.”* on the property of_________________________________(Name of institution)

I have been informed of the risks and benefits of the investigation and am aware that individuals may withdraw from the study at any time without further consequence. The researcher has been granted permission to conduct his research using our athletes based on written and informed consent by the participants.

Regards,

____

Quinten Potgieter (master’s student) Nelson Mandela University
Human Movement Sciences Department
Summerstrand Campus (South)
Building 125
Port Elizabeth 6031, South Africa
Email: s214041824@mandela.ac.za

APPENDIX H – STEP BY STEP TEST PROTOCOL

1. Researcher to explain the study and physical demands to participant (Appendix B).
2. Participant to fill out and sign consent form (Appendix C).
3. Participant to fill out and sign medical history form (Appendix D).
4. Researcher to palpate sites on *quadriceps*. Once palpated researcher can place electrodes (Verbal consent will be asked by the researcher, if necessary, to shave leg hair at electrode site).
5. Researcher to explain, demonstrate and allow one familiarisation example of the SEBT and NMF protocol as well as when NMF criteria will be met.
6. Participant to start warm up procedure.
7. Researcher to attach electrodes to EMG followed by MVC of *quadriceps* and *hamstring*s of the injured and uninjured sides by the participant.
8. Participant to start SEBT with uninjured lower limb.
9. Participant to perform NMF protocol with uninjured lower limb.
10. Participant to perform another SEBT ASAP after NMF with uninjured lower limb.
11. Participant to rest for 3 minutes during which researcher connects EMG to involved side.
12. Participant to repeat steps 8-10 but with injured lower limb (any sign of discomfort or pain will lead to termination of the test).
13. If no discomfort or pain is experienced by participant after final SEBT under a fatigued state, free to leave as testing is completed.

APPENDIX I – PROOFREADING LETTER

ONE STOP SOLUTION
Professional Editing Services

One Stop Solution
18 Woltemade Street
Kabega Park
Port Elizabeth
6045

www.onestopsolution.co.za

TO WHOM IT MAY CONCERN

I, Redène Noeleen Steenberg, declare that the language editing has been done for the dissertation of:

Name: Quinten Christiaan Potgieter
Student Number: 214041824

entitled:

Knee Joint Competence Post Anterior Cruciate Ligament Reconstruction in Amateur SWD Rugby Players

Submitted in fulfilment of the requirements for the degree Master of Human Movement Science at the Nelson Mandela University.

I cannot guarantee that the changes that I have suggested have been implemented nor do I take responsibility for any other changes or additions that may have been made subsequently.

Any other queries related to the language editing of this treatise may be directed to me at 076 481 8341.

Signed at Port Elizabeth on 24 November 2021

R.N. Steenberg