Swansea University
Prifysgol Abertawe

Neck Strength and Head Acceleration Events in University Women's Rugby Union

Victoria Grace Hayden

Submitted to Swansea University in fulfilment of the requirements of the
Degree of Masters by Research, 2021

Abstract

Women's rugby union has experienced unprecedented growth in recent years, with female players now comprising one-third of the global rugby playing population. Despite these numbers, most existing rugby injury and biomechanics data is derived from androcentric studies that are generalised and applied to female players, regardless of the well-established biomechanical and physiological sex differences. Concussion is a concerning player welfare issue in rugby; however, neck strength is reported to be an important variable in head impact reduction. The primary aim of this thesis was to quantitatively assess neck strength and head acceleration magnitude in female university level players.

Baseline maximal isometric neck strength and endurance of university women's rugby players (*n*=30) were measured using a purpose-built isometric neck strength testing apparatus. The intervention group (*n*=20) then participated in a nine-week neck strengthening training programme before mid-season re-tests. In addition, the magnitude of head acceleration events was recorded for players from the intervention group (*n*=12) during six competitive games using instrumented mouthguards. The influence of neck strength on head acceleration magnitude data was investigated, as well as the contribution of playing position, anthropometric variables, playing experience and the mechanisms of the head acceleration event.

The players recorded limited anthropometric and positional specificity. Of the 73 verified head acceleration events recorded, the median peak linear and rotational acceleration were $11.9 \pm 7.3\ g$ and $830.9 \pm 646.9\ \text{rad}\bullet\text{s}^{-2}$ respectively. Notably, whiplash head-to-ground movements were recorded more frequently that in androcentric studies. There was a positive intervention effect on neck strength, but no correlation between neck strength and head acceleration magnitude.

The findings provide an evidentiary platform of objective data, demonstrating the requirement of female representation in rugby union studies. Safe and effective training interventions for female players, based on female-derived data are pertinent to facilitate the further development of women's rugby.

Declarations and Statements

DECLARATION:

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

Signed [redacted]

Date ....15/09/2021...

STATEMENT 1:

This thesis is the result of my own investigations, except where otherwise stated. Where correction services have been used, the extent and nature of the correction is clearly marked in a footnote(s). Other sources are acknowledged by footnotes giving explicit references. A bibliography is appended.

Signed [redacted]

Date ....15/09/2021...

STATEMENT 2:

I hereby give consent for my thesis, if accepted, to be available for photocopying and for inter-library loan, and for the title and summary to be made available to outside organisations.

Signed [redacted]

Date ....15/09/2021...

STATEMENT 3:

The University's ethical procedures have been followed and, where appropriate, that ethical approval has been granted.

Signed [redacted]

Date ....15/09/2021...

Table of Contents

Acknowledgements

I would like to express my great appreciation to a number of individuals whose continual support made the completion of this thesis possible. Firstly, to my supervisors, Dr Elisabeth Williams, Prof Kelly Mackintosh, Prof Melitta McNarry and Dr Desney Greybe for their knowledge and guidance. I owe them thanks for sharing with me their passion for research and instigating the development of this inquisitee within myself. I wish to thank all members of Swansea University and Cardiff University Women's Rugby Union teams, along with Siwan Lillicrap, George Stevens and Gareth Beer, without whom this research would not have been possible. It has been a privilege to conduct research among a group of individuals with such dedication and enthusiasm for rugby, making the purpose of this thesis ever more valuable. I cannot express enough gratitude for the continued support from Freja Petrie, Madeline Wynn Jones, Georgia Weall and Thomas Pennington and for making the process such an enjoyable one. Lastly, I am forever grateful for my parent's endless encouragement and belief in my ability.

List of Figures

List of Tables

List of Abbreviations

Bks – backs

BM – body mass

BMI – body mass index

BUCS – British universities college sport

CIRC. - circumference

COVID-19 – corona virus disease 2019

CTE – chronic traumatic encephalopathy

Ext - extension

Flx - flexion

Fwds – forwards

GSI – Gadd severity index

HAE – Head acceleration event

HC – head circumference

HIA – head impact assessment

HIC – head injury criterion

iMG – instrumented mouthguard

INSTA - isometric neck strength testing apparatus

IMU – inertial measurement unit

L-Flx – left lateral flexion

LOC – loss of consciousness

MANOVA – multivariate analysis of variance

mTBI – mild traumatic brain injury

MVC – maximal voluntary contraction

Nat. – National

NC – neck circumference

NE – neck strength endurance

NFL – national football league

N:H – neck-to-head circumference ratio

NS – neck strength

NSTP – neck strengthening training programme

PAR-Q – physical activity readiness questionnaire

PLA – peak linear acceleration

PRA – peak rotational acceleration

Prem. – Premiership

PRISP – professional male rugby injury surveillance project

PRV – peak rotational velocity

Reg. Regional

R-Flx – right lateral flexion

RTP – return to play

SCAT – sports concussion assessment tool

SCM - sternocleidomastoid

SB – shoulder breadth

SH – standing height

SRC – sports-related concussion

TAI – traumatic axonal injury

TBI – traumatic brain injury

TTF – time to fatigue

TZ – trapezius

US – United States

WRISP – women’s rugby injury surveillance project

WSTC – Wayne state tolerance curve

Yrs. - years

Chapter 1: Introduction

1.1 Research Context and Background Literature

Concussion, classified as a mild traumatic brain injury (mTBI; Hon, Leung, & Torres, 2019), can be highly unpredictable resulting in numerous disparate definitions. However, it is well accepted that the cranium must undergo linear and rotational acceleration (Bigham & Hanlon, 2020). Potential symptoms include, but are not limited to, loss of consciousness, disorientation, nausea and sleep disturbances (Sinnott, Kontos, Collins, & Ortega, 2020). Despite limited understanding of its pathophysiological underpinning, sports-related concussion (SRC) is a well-documented clinical entity (McCrory, Feddermann-Demont, et al., 2017) and therefore a major public health concern, particularly for contact and collision sports.

Rugby Union is characterised by contact events, including rucks, mauls and scrums. The sports composition, irrespective of gender, instigates repeated direct and indirect head acceleration events (HAE; King, Hume, Brughelli, & Gissane, 2015), with greater collision demands for forward positions, in comparison to backs (Dubois et al., 2017). Although the cumulative effect and long-term implications of mTBI is relatively unknown, symptoms persist from approximately 15% of concussions (Tator et al., 2016). Moreover, repercussions can arise years to decades after a latent period following repetitive mTBI (Bailes, Turner, Lucke-Wold, Patel, & Lee, 2015). Indeed, chronic traumatic encephalopathy (CTE), a progressive neurodegenerative disease, has frequently been diagnosed in retired rugby players (Stewart, McNamara, Lawlor, Hutchinson, & Farrell, 2016).

There has been an accelerated rate of participation within women's rugby in recent years, with England Rugby (2019) reporting over 2.7 million players worldwide. The professionalisation of the first women's players in 2019 (Rees, 2018) instigated significant growth in the number of amateur level participants (Donnelly, 2018). Changes to the anthropometry of higher-level women's rugby players as a result of their professionalisation are yet to be recorded, but are documented in higher-level male players following the professionalisation of men's rugby in 1995 (Nyberg & Penpraze, 2016). Despite the rapid growth in participant numbers, it is pertinent to note that for women, limited early exposure to contact sports participation, results in variations to their game style and a different interpretation of rugby (Dovey, 2016). Moreover, females have been shown to have a greater likelihood of obtaining a SRC, with the resultant symptoms more severe than their male counterparts (McGroarty, Brown, & Mulcahey, 2020). Taken together, expeditious research is warranted to ascertain how these differences should be reflected within women's rugby training and the rules of the game.

The distinct, phenotypic differences between males and females is referred to as sexual dimorphism (Costello, Bieuzen, & Bleakley, 2014). It is noteworthy that, according to World Rugby (2020), 'female' refers to individuals who were assigned this biological sex at birth and have biologically female physiology. More specifically, those referred to as female do not produce testosterone levels commensurate of males during puberty or experience the resultant androgenising effect (World Rugby, 2020f). Whereas, 'women' refers to anyone who identifies as a woman, regardless of whether they are biologically female or not (World Rugby, 2020f). Sex differences in head impact biomechanics can be attributed to the specific composition of the cervical spine and musculature (Stemper & Derosia, 2009). Indeed, studies have found maximal neck strength (NS) to be lower in females than males (McGroarty, Brown, & Mulcahey, 2020). Due to the influence of NS on head motion (Wood, Morrison, & Sosnoff, 2019), NS and speed of neck musculature activation have been identified as mechanisms predictive of SRC (Wood et al., 2019). It is therefore imperative that sex-specific research be conducted on rugby players to account for females lower biomechanical threshold for concussion (McGroarty et al., 2020).

There is a growing body of literature on concussion and NS; however, a gender data gap exists as there is scant research in females (Woitowich & Woodruff, 2019). This shortage also applies to anthropometric research, used to identify precursors to injury and optimise performance, such as through appropriate positional allocation (Nyberg & Penpraze, 2016). Whilst inappropriate, research conducted on male players is currently generalised to females, from which game demands and recovery strategies are estimated (Clarke, 2016). In recent years, alterations to World Rugby's rules and changes to coaching methods have been applied across both men and women's rugby, with the aim of lowering concussion prevalence. This includes the implementation of head impact assessments

(HIA) and return to play (RTP) regulations (McGroarty et al., 2020). However, the rate of concussion has not fallen in women's rugby (O'Regan, 2019; WRISP, 2018) or men's rugby (PRISP, 2018). It is therefore critical that the prominent factors which contribute to the severity and frequency of HAE in women's rugby be investigated. Specifically, the association between anthropometrics, NS and telemetry data on the kinematics and magnitude of HAE's. Studies in men's rugby have concluded that stronger neck musculature can significantly decrease neck flexion (Flx) and extension (Ext) (Nightingale, Myers, & Yoganandan, 2015), with the capability of reducing head impact magnitude and concussion likelihood (Collins et al., 2014).

Given that neck injuries and head kinematics can be alleviated by improving NS (Dezman, Ledet, & Kerr, 2013; Mansell, Tierney, Sitler, Swanik, & Stearne, 2005), neck strengthening training programmes (NSTP's) are being utilised. The fundamental purpose of NS interventions is to prevent cervical and concussive injuries from occurring and reduce the severity of injuries that do arise. However, there is a dearth of literature evaluating their effectiveness, likely due to, at least in part, to the absence of an effective method of measuring NS (Dvir & Prushansky, 2008). Recent literature has supported the use of fixed-frame dynamometry, particularly custom-built isometric NS testing apparatus using load cells (Mcbride & Oxford, 2020). This method is reported to have excellent reliability and safety when investigating the relationship between NS and injury prevalence (Hall, Morissette, Cordingley, & Leiter, 2017), opposed to hand held dynamometry, for example Gatherer systems (Hamilton & Gatherer, 2014). To date, isometric NS testing protocols have been conducted in seated, standing, prone and supine positions (Salmon et al., 2015), and are therefore not functionally relevant to rugby. To be applicable to rugby, a neutral horizontal testing position must be adopted (Salmon et al., 2015), in accord with the majority of cervical loading that occurs in games (Salmon et al., 2015). Having a rugby-specific assessment of NS would not only facilitate inter-study comparisons, but enable the establishment of a normative NS database (Nyberg & Penpraze, 2016).

1.2 Research Objectives

The main objectives of this thesis were as follows:

- Quantify neck strength in female university rugby union players, using a highly repeatable method.
- Quantify and characterise on-field head acceleration events in these players, using well coupled inertial sensors.
- Improve the understanding of head acceleration magnitude and mechanism as a function of neck strength, and contributory factors such as playing position, anthropometrics and rugby playing experience.

1.3 Structure of Thesis

Chapter 2: Review of Literature delivers a background to the study area and provides the rationale for this thesis. Examination is centred on seven fundamental areas. Chapter 2.1 begins by affirming the extent of the gender data gap and emphasises the damaging implications of females being under-researched. Chapter 2.2 explains rugby's core elements and values, the delay in women's injury prevalence research and the rapid evolution of the women's game. In Chapter 2.3, concussion and traumatic brain injury (TBI) are explained in respect to rugby union and specifically, females. Chapter 2.4 demonstrates that the long-term risks of TBI, can be life-limiting or life-threatening, stressing why appropriate detection methods and monitoring practices are paramount. Chapter 2.5 focuses on methods of reducing TBI in sport. Reasoning for sex disparities in prevalence are investigated in Chapter 2.6 which overviews male and female head and neck anatomy. Chapter 2.7 explores the association between NS and injury prevention and ultimately, how improving the NS of women's rugby players through training is beneficial.

The methodology (**Chapter 3**) outlines details on the participants, anthropometric testing, isometric NS and NE assessments, the neck strengthening training programme, head acceleration event valuation and statistical analysis. Following this, the thesis findings are presented in the results (**Chapter 4**). Lastly, the discussion (**Chapter 5**), composed of seven sections, aims to evaluate the reasoning behind and the potential implications of the results. Chapter 5.1 begins by discussion anthropometric and positional specificity. Chapter 5.2 quantifies head acceleration events in female rugby athletes. Chapter 5.3

examines the effectiveness of NS training, before NS is investigated as a method of reducing head acceleration events in Chapter 5.4. Future research directions are investigated in Chapter 5.5 and the methodological limitations outlined in Chapter 5.6. Lastly, Chapter 5.7, presents the final conclusions of this thesis.

Chapter 2: Review of Literature

2.1 Female Representation in Sports Science Literature

2.1.1 Gender Data Gap in Scientific and Medical Research

Robust biological differences between males and females affect health and wellbeing, medical care, disease, injury epidemiology and sports performance (Costello et al., 2014; Rauen et al., 2020). Nevertheless, there is systematic underfunding of female participants in research (Holdcroft, 2007), which may stem from the underemployment of females in science, engineering, medicine and on editorial boards (Colwell, Bear, & Helman, 2020). Androcentric research is therefore often generalised and applied to females, leading to perhaps erroneous diagnoses, and subsequently incorrect dosage and treatment recommendations (Hoel et al., 2009; Makama, Garba, & Ameh, 2012). Whilst this is of concern across all medical research, the scant literature in females is most prominent in sport and exercise-related studies (Costello et al., 2014). Specifically, females only accounted for 35-37% of six million participants published over a three-year period (Costello et al., 2014). By 2018, female inclusion in clinical studies had increased to 49% (Feldman et al., 2019) but remains unrepresentative of the number of individuals diagnosed with each disease/ condition (El-Menyar et al., 2014). There is a plethora of research demonstrating that sex is a crucial variable in injury biomarkers, risk factors, symptomatology, progression and treatment responses (Ferretti et al., 2018; Simon, 2005) due to sexual dimorphism, which describes phenotypic differences between male and females (Reider, 2012). This therefore suggests that the adoption of a precision medicine approach, creating tailored, preventative and therapeutic sex-specific strategies, as opposed to the existing all-encompassing strategies, is urgently required (Cirillo et al., 2020).

2.1.2 Sex Differences in Sports Concussion Literature

Rugby Union (hereafter referred to as ‘rugby’) represents an extreme example of the gender data gap, directly related to the lower participation rates in women’s contact sports (Emmonds, Heyward, & Jones, 2019). In 2018, males represented 72% of total rugby players (World Rugby, 2018b). Thus, there is a fundamental flaw in the evidence base relating to traumatic brain injury (TBI) in women’s rugby, where sex differences in prevalence, symptoms and response to concussive injury and brain structure have been reported (Covassin, Elbin, Harris, Parker, & Kontos, 2012; Ferretti et al., 2018).

However, the role of sex on neuropathological manifestations remains inconclusive (Ferretti et al., 2018). Given that adult males have a lower fat mass, larger and stronger bones, and greater arm muscle mass than females (Wells, 2007), it could be postulated that they influence injury likelihood, nature and severity in rugby (World Rugby, 2020e). Urgent sex-specific research is required to improve societal equality in performance capabilities (Tannenbaum, Ellis, Eyssel, Zou, & Schiebinger, 2019) and to support female clinical guidelines (Hoel et al., 2009; Holdcroft, 2007; Makama et al., 2012).

2.2 Rugby Union Background

2.2.1 Benefits of Rugby Union to Communities and Health

Rugby Union's Players, Composition and Benefits

Rugby is played by men, women, and children, from grass root to professional level. The rules and structure within the adult game (>18 years) are identical for men and women (World Rugby, 2020b). This is potentially problematic due to sex differences increasing the injury risk for females (McGroarty et al., 2020), and the lack of data supporting the applicability of male-derived studies to female players (Clarke, 2016). The element of concern is that rugby permits full contact, with a typical game incorporating high-intensity movements, including sprints, mauls, rucks and tackles, as well as events of lower intensity, such as jogging and walking (Roberts, Trewartha, Higgitt, El-Abd, & Stokes, 2008). The player's positions are categorised into forwards and backs, which have different physical requirements regarding cardiovascular fitness, muscular endurance and strength, speed and agility (Singa, Pitil, Juliana, & Wahed, 2020). Despite being detrimental to injury prevalence, inclusivity of a range of somatotypes on a rugby team is therefore advantageous to performance (Kearney, 2017), a reflection of World Rugby's principle that rugby is a 'Sport for All' (World Rugby, 2020c).

Sport, Women and Rugby

Historically, sport was perceived as a highly masculine domain; particularly contact sports (Toffoletti & Palmer, 2019). The gendering of sports has since occurred, influenced by the degree of contact or aesthetics and perceived masculinity or femininity of sporting stereotypes (United Nations, 2007), dictating the appropriateness of each genders participation (Women in Sport, 2019). More recently, changing attitudes has contributed to the increased range of sports in which females are encouraged to compete (Clarke, 2016). As a result, women's participation statistics have dramatically increased, from 2.2% of total participants in the 1900 Summer Olympic Games (IOC, 2016) to 44% at London 2012, and a predicted 49% for Tokyo 2020 (IOC, 2020).

The growth of women's rugby has challenged the cultural and sociological forces that previously steered females away from contact sports, as well as the misconception that certain visible qualities of athleticism are inherently masculine (Clarke, 2016; Lough & Geurin, 2019). Rugby appeals to prospective participants because it is not a physique-salient sport and does not conform to many expected female stereotypes arising from societal conditioning (Women in Sport, 2019). This includes not abiding by solely feminine traits, nor being pressured to wear sexualised sportswear (Nemeth, Park, & Mendle, 2020). Unusually, rugby challenges societal expectation by enabling women to be portrayed as physically and mentally strong, determined and assertive (United Nations, 2007). The adoption of this attitude outside of the field of play is what makes female rugby players excellent role models for young girls, regardless of whether they are athletic (Meier, 2015). The recent growth of women's rugby's, coupled with the positive impact on individuals and society unattainable from other sports (Baumann, 2013), supports the need to conduct sex-specific research to ensure safe, female participation.

2.2.2 Reported Injury Trends

Sex Differences in Injury Prevalence Data

Rugby's full-contact nature contributes to it having the highest injury prevalence of all professional team sports (Brooks & Kemp, 2008). Despite this, the majority of injury epidemiology data is derived from male cohorts (Williams, Trewartha, Kemp, & Stokes, 2013) due to, at least in part, more established injury reporting systems, funding and resources (Quarrie, Hopkins, Anthony, & Gill, 2013). Studies on women's rugby, which are beginning to emerge, show different injury prevalence rates to those previously found for the men (King et al., 2019).

The professional rugby injury surveillance project (PRISP), organised in 2002, is the longest running rugby injury surveillance programme for males (PRISP, 2018). During the 2017-18 season, premiership and senior clubs recorded 92 match injuries per 1,000 playing hours. On average, 37 days were taken to return to play (PRISP, 2018).

Concussion was the most frequently reported injury, at a rate of 18 per 1,000 match hours, accounting for 20% (PRISP, 2018). Given the anatomical and physiological sex differences (Stemper et al., 2009), these findings may not be applicable to female players. As such, female-specific data is required.

The founding of the women's rugby injury surveillance project (WRISP; WRISP, 2018) is a substantial development in addressing the gender data gap in rugby. The first WRISP reported data, aligning with the 2017-18 season, was 36 match injuries per 1,000 hours for elite (premier league) women (WRISP, 2018). The authors postulated that the lower prevalence than men may be due to a reluctance to report minor injuries (WRISP, 2018). Conversely, data revealed a higher average of 66 days was taken to return to play, in comparison to men. Such discrepancies may diminish with the increased reporting of minor injuries (WRISP, 2018). Consistent with the findings from male players, concussion was the most common injury, accounting for 19% of injuries, although reported at a lower rate of 7 per 1,000 hours (WRISP, 2018).

Additional Factors Affecting Injury Prevalence Data

Injury prevalence data is only applicable to the population and participation level from which it was obtained, as motivation and playing intensity are heavily influenced by sub-categories other than sex (Williams et al., 2013). Yet, despite the importance of understanding injuries in order to reduce incidence and indeed severity, there is a dearth of research in women's rugby. A higher injury incident rate is reported in elite male players (Jakoet & Noakes, 1998; Williams et al., 2013) compared to community-level male players (Roberts, Trewartha, England, Shaddick, & Stokes, 2013). The scarce women's rugby research today, is largely conducted in amateur players, with fewer resources and research funding (Gabb, 2018), thereby precluding inter-sex comparisons. It is; however, noteworthy that in men's rugby incident rates for professional players is shown to differ between competitive games and training, at 81 and three injuries per 1,000 player hours, respectively (Williams et al., 2013). During the 2010 World Cup, the risk of competitive game injury was lower for women than men (Taylor, Fuller, & Molloy, 2011). The few studies within women's rugby have reported a game injury rate between 17.1 and 37.5 per 1,000 hours, with training-related injuries ranging from 1.0 to 3.0 per 1,000 hours (King et al., 2019).

Male-focused studies have found the most frequent injury location to be the upper limb (14 per 1,000 player hours), followed by the head (13 per 1,000 player hours) and trunk (9 per 1,000 player hours; Williams et al., 2013). The most common injury type in men's rugby was muscle/tendon injuries (40 per 1,000 player hours), followed by joint/ligament (34 per 1,000 player hours), central/peripheral nervous system (8 per 1,000 hours) and fractures/bone stress injuries (4 per 1,000 hours; Williams et al., 2013). An absence of female data precludes inter-sex comparisons. For male players, positional comparisons have shown higher incidence rates in forwards (Bathgate, Best, Craig, & Jamieson, 2002; Best, McIntosh, & Savage, 2005), with others reporting no positional differences (Williams et al., 2013). John, Brooks and Kemp (2008) concluded that inter-player position disparities may relate to the location and type of injuries, as opposed to their frequency, attributed to position-specific demands (Cahill, Lamb, Worsfold, Headey, & Murray, 2013).

Studies of male players have highlighted a greater injury prevalence during the third quarter of games (Williams et al., 2013) and more neck injuries later in games (Fuller, Brooks, & Kemp, 2007), though the application of these findings to female players is unknown. Moreover, male-focused rugby studies have reported an increased injury incident rate in recent years in Premiership rugby (Brooks & Kemp, 2011). An injury rate of 75 per 1,000 hours was reported between 2005 and 2006, increasing to 100 injuries per 1,000 player hours between 2008-2009 (Brooks & Kemp, 2011). Longitudinal female-focused injury literature is required in order to facilitate the analysis of injury trends over time.

2.2.3 Professionalisation of Rugby Union

Rugby is played by over 9.1 million people (World Rugby, 2018a), in over 129 countries (Hume et al., 2016). The professionalisation of the men's game was in 1995 (Williams et al., 2013) and had a substantial impact, improving the players capabilities including muscular strength, speed, power and fitness (Duthie, Pyne, & Hooper, 2003; Sedeaud et al., 2012). Consequently, male players anthropometry has changed since the professionalisation of men's rugby (Nyberg & Penpraze, 2016) due to additional training hours and increased exposure to the games demands. Alterations to the game structure enabled the ball to be in play for longer (Gardner et al., 2014). Subsequently, the speed and magnitude of contact events increased, with research showing that contact events were four times more frequent (Austin, Gabbett, & Jenkins, 2011; Eaves & Hughes, 2003; Quarrie & Hopkins, 2007). Such changes were identified as having negative repercussions on the physiological demands on male players (Eaves & Hughes, 2003).

Addressing the negative aspects connected with the professionalisation of men's rugby will aid the positive development of women's rugby, where participant rates are accelerating due to World Rugby's Women's Plan 2017-25 (World Rugby, 2020a). This is opportune as only a minority group of women's 15 players began professional full-time contracts in January 2019 (Rees, 2018). Members of the women's 7's team have been recipients of full-time contracts since 2014 (Rugby, 2014). In particular, the 'Get into Rugby' programme encouraged new, long-term players, of which 39% were women (World Rugby, 2020a). Consequently, 2.7 million women now account for more than a quarter of global rugby players (World Rugby, 2018b), an increase of 60% since 2013 (World Rugby, 2018a). Despite the developments, large pay disparities remain between men and women of equal standards. The greatest inequality in prize money for sporting events is most evident in the 2020 Six Nations rugby tournament. The winning team in the men's competition received £5 million, but in the women's competition there were no financial rewards. The increase in grass root players will soon be reflected at elite and professional levels. Without equal opportunities, however, the resources available to conduct research on women rugby players will remain lower than for men.

2.3 Head impacts in Rugby Union and Other Contact Sports

2.3.1 Defining Concussion and Traumatic Brain Injury

Conducting concussive research requires specific and well defined and understood terminology. Sports-related concussion (SRC) is defined in the concussion consensus statement as a complex pathophysiological process affecting the brain, induced by traumatic biomechanical forces, directly received or transmitted to the head from any bodily region (McCrory et al., 2017). Incorrectly, the terms concussion and traumatic brain injury (TBI) are used interchangeably; however, concussion is a subset of TBI, which has three levels of classification: mild TBI (mTBI; concussion), moderate TBI and severe TBI (coma; Brain Trauma Foundation, 2020).

The wide-ranging symptoms and indefinite prevalence duration of mTBI mean it is difficult to recognise and record (McCrea, Hammeke, Olsen, Leo, & Guskiewicz, 2004). Indeed, the concussion consensus statement highlights that neurological impairments may not be immediate, loss of consciousness (LOC) does not always occur, and symptoms can be short lasting or prolonged (McCrory et al., 2017). Previously, definitions have placed too heavy focus on the duration of LOC and post-traumatic amnesia symptoms (Borg et al., 2004; Winsper et al., 2013), falsely suggesting that LOC is a requirement of concussion. This was the belief of 40% of rugby league coaches and support personnel (King & Hume, 2010), which is concerning given that 90% of SRC's are not associated with LOC (Scorza, Raleigh, & O'connor, 2012). Consequently, 50-90% of rugby concussions likely went undetected or undiagnosed prior to 2005, with necessary medical attention not pursued (Gardner et al., 2014). It is therefore noteworthy that TBI prevalence represented using hospitalisation figures is likely misrepresentative of the true number of concussions (Cassidy et al., 2004). Research utilising more precise detection techniques is therefore warranted.

2.3.2 Reported Incidents of Mild Traumatic Brain Injury in Sport

TBI prevalence was previously perceived higher for males, reflective of male's greater exposure and higher participation rates in collision sports, including rugby (Haarbauer-Krupa et al., 2018). Yet, epidemiological research conducted across contact and non-contact sports, which accounted for participation numbers, provides a strong evidence basis that females have a higher rate of SRC (Abrahams, McFie, Patricios, Posthumus, & September, 2014; Benedict et al., 2015; Covassin, Swanikt, & Sachs, 2003; Dick, 2009), 1.4 times higher in sex-comparable sports (Covassin, Moran, & Elbin, 2016).

Non-contact sports exhibit high concussion severities but low frequencies (Pfister, Pfister, Hagel, Ghali, & Ronksley, 2016). However, equestrianism is an anomaly, as concussion is the most severe and frequent injury (Thomas, Annest, Gilchrist, & Bixby-Hammett, 2006). Kuhl et al. (2014) found that, in line with contact sports, almost half of a population of competitive equestrian athletes, 71% composed of females, were predicted to sustain a concussion during their career. In contrast, contact sports have high concussion frequencies and cause an estimated 45% of sports-and recreational-related TBI among children in the US (Lumba-Brown et al., 2018). Sex-disaggregated data on ice hockey shows a higher concussion rate of 0.82 per 1,000 athlete exposures for women, than 0.72 per 1,000 for men (Agel & Harvey, 2010). Direct player contact caused 72% of the men's concussions, compared to 41% of the females (Agel & Harvey, 2010). These sex-disparities in impact-causing events are coherent with rugby studies, illustrating that females obtain more concussions from events other than direct player impacts, such as contact with the ground.

2.3.3 Detection of Traumatic Brain Injury in Rugby

Education is fundamental for recognising TBI and thus reducing complications (McCrory, 2017). World Rugby, formerly the International Rugby Board, developed an online programme entitled 'recognise and remove' in 2014 (IRB, 2016) and The Rugby Football Union's HEADCASE programme is acknowledged as a leading detection and management resource (RFU, 2018). However, these courses are not utilised to their full advantage, with only 5.5% of Irish rugby clubs using online head impact evaluation programmes (Coughlan, Fullen, & McCarthy, 2014). This called for side-line assessment tools with greater objectivity. First, rugby law now requires head impact assessments (HIA) following a suspected concussion before permitting return to play (RTP) (World Rugby, 2015). Second, the Sports Concussion Assessment Tool (SCAT) is used by healthcare specialists to identify concussion immediately following an impact (McCrory et al., 2013). Although, the most recent version, SCAT5, still has limited application in assisting RTP and monitoring recovery, as its validity can be reduced by bias and it is generalised to large populations including different sports, disabilities, ages and sexes (Echemendia et al., 2017). Sex-specific assessment tools are required to improve TBI detection and enable appropriate evaluation of concussion reduction methods.

2.3.4 Reported Incidents of Mild Traumatic Brain Injury in Rugby

It is common to obtain a mTBI whilst playing rugby (Selenke, 2020), with studies regularly reporting concussion as the most prevalent injury (Fuller, Taylor, Kemp, & Raftery, 2017; Kerr et al., 2008; Yeomans et al., 2020). In professional men's rugby, concussion was the most frequent injury for seven consecutive seasons (PRISP, 2018). Moreover, prevalence has increased over the past decade, attributed to improved detection, as well as an increased number of events (Langevin et al., 2020). SRC from playing rugby accounted for the most injury entitlement claims to The Accident

Compensation Corporation in New Zealand between 2001 and 2011 (King, Gissane, Brughelli, Hume, & Harawira, 2014). Claims are influenced by concussion knowledge and management, anatomical differences and optimisation of injury support (Bloom, Loughead, Shapcott, Johnston, & Delaney, 2008). Nevertheless, mTBI prevalence in rugby is consistently and concerningly high, necessitating new reduction strategies.

Sex Differences in Rugby Concussion Prevalence Data

The limited data collected within women's rugby indicates that, irrespective of a training or game setting, the rate of obtaining a concussion is lower than in men's rugby (Kerr et al., 2008). Concussion prevalence is also disparate between training and games, due to different playing intensities and the presence of medical personnel at games increasing TBI detection. During training, the concussion rate for males and females is 0.37 compared to 0.30 per 1,000 player practice hours respectively (Kerr et al., 2008). During games, males and females sustained concussions at 2.16 and 1.58 per 1,000 player hours respectively (Kerr et al., 2008). Conversely, a higher female prevalence is recorded in rugby-7's, at 0.55 per 1,000 player hours, compared to 3.01 per 1,000 player hours for males (Gardner et al., 2014).

Additional Factors Affecting Rugby Concussion Prevalence Data

In addition to sex, it is important to distinguish between other factors influencing concussion prevalence. Incident statistics on women's rugby are extremely limited, yet numerous studies on males, who abide by identical rules, show variations between sub-categories, including player position, age, experience and playing conditions. However, it is important to emphasise that women's incidence values and injury severity may differ, hence longitudinal, female research is required. Improvements in SRC monitoring over time may indicate an increased TBI frequency. However, in men's rugby, a meta-analysis over three decades by Gardner et al. (2014) found no rise in concussion incidents.

Numerous male studies record a lower concussion risk in forwards (4.02 per 1,000 hours) than backs (4.85 per 1,000 hours; Brooks, Fuller, Kemp, & Reddin, 2005; Gardner et al., 2014; Owens et al., 2019). Regardless of position, a greater TBI prevalence, with longer lasting symptoms and higher likelihood of developing second impact syndrome is recorded in children compared to adults (Harmon et al., 2013). Youth match incident SRC rates range from 0.2 to 6.9 per 1,000 player hours (Kirkwood, Parekh, Ofori-Asenso, & Pollock, 2015); however, studies of children have failed to segregate the data by sex. Studies conducted on males present contrasting findings on the effect of player level on SRC prevalence. A higher concussion rate has been recorded in professional (premiership) males (4.1 per 1,000 match hours) compared to community RFU level 3-9 players (1.2 per 1,000 match hours; Kemp, Hudson, Brooks, & Fuller, 2008; Roberts et al., 2013). Although a greater rate of concussion is also recorded in amateur males (0.62 per 1,000 match hours) than elite (0.40 per 1,000 match hours; Gardner et al., 2014).

The effect of funding disparities between men's and women's rugby, often evident in playing conditions, has also been investigated. Concussion probability has been found to increase (Chalmers, Samaranayaka, Gulliver, & McNoe, 2011), yet also be unaffected by ground hardness (Owens et al., 2019; Takemura, Schneiders, Bell, & Milburn, 2007). Additionally, a higher concussion rate was attained by professional males on grass, opposed to the increasingly installed, artificial turf (Ranson, George, Rafferty, Miles, & Moore, 2018).

2.3.5 Returning to Play Following Traumatic Brain Injury in Rugby

Full recovery before resuming play is vital (McCrory, Meeuwisse, Aubry, Cantu, Dvořák, et al., 2013). However, conflicting advice between The World Rugby Handbooks medical guidance (World Rugby, 2016) and concussion guidelines has caused confusion (Boffano et al., 2011) and a reduced policy adherence by players and coaches. Consequently, following TBI, 52% of high school players decided themselves when to RTP (Sye, Sullivan, & McCrory, 2006). Of community players, following TBI, 34% remained on the field for the game duration, whilst 48% temporarily left the field but resumed playing the same game (Hollis, Stevenson, McIntosh, Shores, & Finch, 2012). Whilst the World Rugby handbook has separate guidelines for children and adolescents (World Rugby, 2016), there remains no female-specific guidelines. Successful RTP also requires regular communication between players, medical practitioners, support personnel and stakeholders, throughout the period between concussion recognition and RTP (Salmon et al., 2020). Of importance, a phone application and web-based portal utilised in New Zealand is improving player welfare by aiding the assessment, recording and management of concussion (Salmon et al., 2020). Sex-disaggregated research using valid monitoring techniques is required to ascertain whether females are cognitively and physically different and respond differently to TBI than males (McGroarty et al., 2020). This will support the development of RTP guidelines specific to females.

2.4 Long-Term Risks of Contact Sport Participation

2.4.1 Sex Differences in Brain Anatomy Influencing Traumatic Axonal Injury Outcome

In recent years, structural differences have been found between male and female brains (Dollé et al., 2018). The Corpus Callosum, the largest white matter structure, consists of 200-250 million axons (Park et al., 2017) and has a larger posterior portion (splenium) in females than males (De Lacoste-Utamsing & Holloway, 1982). The 20-30 billion neurone cells in the brain are each composed of a cell body, an axon and dendrites (Mountcastle, 1998). Axons are located in white matter (Alexander et al., 2010) and axonal pathways interconnect neurones (Hagmann et al., 2008). Neurones primary function is information processing (Koch & Segev, 2000), which enables communication throughout the brains frontal, temporal, parietal and occipital lobes (Jawabri & Sharma, 2020) to all over the body (Koch & Segev, 2000). During trauma, axons are prone to mechanical damage and physiological dysfunction (Tang-Schomer, Johnson, Baas, Stewart, & Smith, 2012).

Sex differences in axon structure influences their susceptibility to damage. More axons (Aboitiz, Scheibel, Fisher, & Zaidel, 1992) with smaller diameters and fewer microtubules have been found in female brains by examining the corpus callosum in both rats (Pesaresi et al., 2015) and humans (Alexander et al., 2010; Dollé et al., 2018). Axons with smaller microtubule diameters fail at lower strain-rates causing more abundant and larger undulations per axon (Dollé et al., 2018). Hence, during trauma, the damage is not identical for male and female brains, with computational modelling revealing that microtubules in female axons are more likely to fail when placed under the same load during trauma (Dollé et al., 2018). Following axon deformation, elevated calcium and sodium levels are believed to cause signalling impairments to axonal transport (Iwata et al., 2004) and subsequent damage (Wolf, Stys, Lusardi, Meaney, & Smith, 2001). In females, axons have greater swelling and a more significant reduction in calcium signalling is evident 24-hours following TBI (Dollé et al., 2018). Pathophysiological disruption to the brain, including the interference to axonal transport due to traumatic axonal injury (TAI), is often the most common underlying cause of long-term concussive symptoms (Johnson, Stewart, & Smith, 2013).

2.4.2 Post-Concussive Symptoms

With a greater understanding of the short-term cognitive response to trauma, there is growing concern regarding the long-term implications (Gardner et al., 2014), which are among the least understood of all injuries in sports medicine (Owens et al., 2019). In 80-90% of cases, concussive symptoms dissipate within seven to 10 days (McCrory et al., 2013) and normal functional abilities return after two to four weeks (Maas, Stocchetti, & Bullock, 2008). However, for some individuals, physical, emotional or cognitive symptoms, such as a reduced functioning of the central and peripheral nervous system (Mathias & Alvaro, 2012), persist beyond the expected recovery time (post-concussive syndrome; Mayo Clinic, 2020). There is also a strong correlation between recent concussion and rate of concussion reoccurrence (Hind et al., 2020; Marshall et al., 2015), which without full recovery, increases the risk of cerebral swelling (second impact syndrome; Kirkwood et al., 2015).

TBI is consistently associated with an increased probability of future health complications (Limb, 2014; Guskiewicz et al., 2007) and the memory deterioration, depression, reduced verbal fluency, irritability and personality change are comparable to Alzheimer’s disease (McMillan et al., 2017). In male rugby players, poorer cognitive functioning has been detected three months after repeated concussions (Gardner, Shores, & Batchelor, 2010) and the neurogenerative disease, chronic traumatic encephalopathy (CTE), years to decades following contact sport participation (Gavett, Stern, & McKee, 2011). CTE symptoms include aggression, depression and short-term memory loss (Mckee et al., 2010), advancing to speech and gait abnormalities, dementia and Parkinson’s disease (McKee et al., 2013), often causing CTE misdiagnosis (Gavett et al., 2011). At present, the effect of the brains anatomical sex-differences on structural and functional brain changes following TBI are unknown.

2.4.3 Detection of the Long-Term Risks of Traumatic Brain Injury

Cognitive assessments are used to investigate long-term damage following TBI. However, retired international rugby players have displayed no performance or mental health abnormalities (McMillan et al., 2017). Notably, the subjectivity of self-reported data, associated with reduced reliability, is overcome through an objective post-mortem approach. Post-mortem examination of recipients of numerous concussions has detected CTE (McKee et al., 2013; Mez et al., 2017) and the presence of the structural brain protein, tau (Avila, Lucas, Pérez, & Hernández, 2004). Tau is thought to be a key biological mechanism associated with concussion (Abrahams et al., 2019), with tau levels shown to be elevated for 90 days post TBI (Bogoslovsky et al., 2017). This causes a negative internal response, the loss of neurones (Bramblett et al., 1993) and neurological deficits (Abrahams et al., 2019).

CTE pathology has been identified in 80% of brains from athletes previously subjected to mTBI (McKee et al., 2013), such as in 87% of American football players (Mez et al., 2017), 75% of rugby players and 72% of football players (Wilson, 2019). In comparison, CTE development in the general population is 12% (Wilson, 2019). It is; however, pertinent to note that post-mortem findings may possess bias, as brain banks are more likely to receive brains with cognitive impairment (McKee et al., 2013). Nonetheless, more severe CTE progression has been correlated with a longer playing history (McKee et al., 2013). The higher rate of CTE development in living female research participants is yet to be observed during post-mortem (McKee, 2020). The appeal for female brain donors in 2019 demonstrates the increased awareness that research is required (McKee, 2020), to confirm whether solely mechanical difference in neck anatomy or biological differences are responsible for females increases susceptibility to CTE (Mckee et al., 2010).

Other neurodegenerative disorders often present concurrently with CTE (McKee et al., 2013). An increased rate of Alzheimer’s and motor neurone diseases at time of death has been identified in National Football League (NFL) players (Vanacore, Lehman, Hein, Baron, & Gersic, 2013) and dementia at 50-60 years in the majority of rugby and football players, whose careers spanned 11-32 years (Wilson, 2019). TBI is also connected with an increased risk of death (McMillan, Weir, & Wainman-Lefley, 2014) and early onset mortality (McKee et al., 2013). A death rate approximately three times greater than the general Unites States (US) population was calculated from 3,439 NFL players (Vanacore et al., 2013). This research demonstrates that brain injuries classified as mild can have serious long-term implications (McKee et al., 2013).

2.4.4 Sex Differences in Long-Term Traumatic Brain Injury Outcomes

Females experience different post-concussion symptoms and recovery patterns to males (Colvin et al., 2009; Frommer et al., 2011). Indeed, sex differences in brain atrophy and rates of cognitive decline have been recorded (Ferretti et al., 2018; Manning et al., 2019). Whilst research is limited on the specific anatomical pathways which make females vulnerable to concussion and associated long-term outcomes (Chamard, Lefebvre, Lassonde, & Theoret, 2016; Sicard, Moore, & Ellemberg, 2018), hormonal differences are believed to be influential (Sicard et al., 2018).

Females are reported to have a lower biomechanical threshold tolerance, meaning they sustain worse concussions (McGroarty et al., 2020). This is confirmed by females reporting more severe somatic symptoms, including headaches and dizziness (Brown, Elsass, Miller, Reed, & Reneker, 2015) and performing poorer on cognitive tests than males (Colvin et al., 2009; Sicard et al., 2018; Tanveer, Zecavati, Delasobera, & Oyegbile, 2017). However, sex differences in cognition are also reported between non-concussed males and females (Covassin et al., 2006; Ferretti et al., 2018; Weiss et al., 2003), so gender norms are important to consider (Colvin et al., 2009).

The severity of long-term outcomes and the lasting brain damage has been shown to be greater in females (Bazarian & Atabaki, 2001; Broshek et al., 2005; Dollé et al., 2018; Sinnott et al., 2020) In males, magnetic resonance imaging (MRI) has revealed a lower mean diffusivity in concussed athletes compared to non-concussed athletes (Chamard et al., 2016), particularly in the corpus callosum where there was significant long-term damage to white matter (Chamard et al., 2016). Similarly, MRI data obtained from women's rugby players six-months post-concussion, detected white matter abnormalities (Manning et al., 2019). Further research is required to understand the effect of structural brain differences on the long-term TBI outcomes including severity and duration.

2.5 Methods of Reducing Traumatic Brain Injury in Sport

2.5.1 Equipment and Rules to Protect Players

Protective Equipment

World Rugby Regulation 12 permits the use of mouthguards, headgear, shin guards, shoulder pads, corrective goggles and, for women, chest pads (World Rugby Handbook, 2019). Protective equipment is worn to attenuate biomechanical force, but offers no protection from major injuries and may even increase injury rates by elevating competitiveness and risk-taking behaviour (Gardner, Quarrie, & Iverson, 2019; Garraway, Lee, Hutton, Russell, & Macleod, 2000). More confident play was reported by 67% of male rugby players wearing headgear (Finch, McIntosh, & McCrory, 2001) and 62% believed headgear could prevent concussion (Pettersen, 2002), yet evidence of this is inconclusive (Gardner et al., 2014). Moreover, this false sense of security is demonstrated in American Football, where improved head protection caused an increase in cervical injury, due to players beginning to tackle with their heads (Nightingale, Myers, & Yoganandan, 2015). Interestingly, in lacrosse, concussion incidents are very similar between the men's contact game and the women's non-contact games, despite wearing helmets and protective padding, and mouthguards only, respectively (Marshall, Guskiewicz, Shankar, McCrea, & Cantu, 2015).

Mouthguards are not mandatory under International Rugby Board law, but custom-fitted mouthguards are strongly recommended (World Rugby Handbook, 2019). Their purpose during direct impacts is to reduce damage to oral structures, absorb shock and decrease SRC risk (Ono, Tanaka, Sako, Tanaka, & Fujimoto, 2020). In New Zealand, dental claims reduced by 43% after mouthguards were mandated by law (Quarrie, Gianotti, Chalmers, & Hopkins, 2005). However, research suggests that mouthguards do not reduce neurocognitive deficits (Mihalik, Bell, Marshall, & Guskiewicz, 2007) and their ability to lessen SRC, LOC and spinal injury is inconclusive (Barbic, Pater, & Brison, 2005). Studies that endorse mouthguard wear are limited by their methodologies, such as using cadavers and skulls secured in fixed positions (McCrory, 2001). Nonetheless, a significant negative association between the frequency of mouthguard wear and SRC incidents has been found (Daneshvar et al., 2011; Ono et al., 2020), particularly from custom-fitted mouthguards (Winters & DeMont, 2014). Although, protective equipment is no substitute for correct performance and safe technique, enforced during games by rules that have been modified to greater protect players. However, it is difficult to optimise performance and prioritise player safety without altering the nature of the game (Williams et al., 2013).

Rule Changes in Rugby

A study conducted by World Rugby in 2016 revealed that the risk of head injury was 4.5 times more likely when the tackle height was above the armpit (Raftery, Tucker, & Falvey, 2020). Additionally, head-injury risk increased by 40% when the tackler was upright and by 36 times during foul play (Raftery et al., 2020). Rule modifications (Carmont, Kelberine, & Lester, 2020; IRB, 2016), guided by The High Tackle Sanction Framework (HTSF), were therefore recently implemented (June 2019; World Rugby, 2019). The HTSF has successfully assisted official's decisions and consistency when issuing sanctions (Raftery et al., 2020), increasing yellow cards issued by 74% and red cards by 138% between 2018-19 (Raftery et al., 2020). Furthermore, amendments to Law 19.10b in 2019 altered the scrum engagement protocol, from a maximum tackle height of the ball carriers shoulder to armpit (Stokes et al., 2019). This was to reduce dangerous amounts of axial or rotational loading to front row players' cervical spines (World Rugby, 2020d). For elite men, this resulted in 30% fewer contact events made to the ball carriers' head and neck by the tackler, but no reduction in concussions (Stokes et al., 2019). The absence of longitudinal women's rugby data means that the effect on women's injury prevalence is unknown.

Unlike rugby, some sports have different rules for men and women, justified by anatomical differences and consequent safety concerns. In ice hockey, checking is prohibited in the women's game, but permissible in the men's (Yard & Comstock, 2006). Concerns have been raised that women are consequently not equipped with the skills needed to anticipate and absorb out-of-control impacts (Agel & Harvey, 2010). This may be reflected in women's rugby, where following a collision, player experience and mastery of fundamental skills can be highly influential in the severity of the outcome. Research on women's rugby may create a future need for sex-specific rules to reduce injury prevalence.

2.5.2 Measuring Exposure to Head Impacts in Rugby

Biomechanical Considerations of Traumatic Brain Injury

Kinematic parameters correspond to the brain's inertial response and are therefore investigated in respect to head impacts (Rowson & Duma, 2013). Peak linear acceleration (PLA) and peak rotational acceleration (PRA) or peak rotational velocity (PRV) are the central parameters relating to brain injury cited in literature (Greybe, Jones, Brown, & Williams, 2020). Linear acceleration is attributed to a temporary intracranial pressure gradient, whereas a strain response is the understood cause of rotational acceleration (King, Yang, Zhang, & Hardy, 2003).

PRA of the head is believed to cause the most injury (Kirkendall, Jordan, & Garrett, 2001), however, PLA and PRA are inter-linked, as the degree of linear acceleration and direction of force corresponds to the extent of rotational acceleration (Rowson & Duma, 2013). Therefore, investigating these components independently is unrepresentative of real head impacts (Rowson, Brolinson, Goforth, & Duma, 2009). In the NFL, PLA and PRA data displays similar profiles for all impact directions, excluding the top of the head (Rowson et al., 2012). Akin to rugby, impacts in NFL are predominantly linearly driven, therefore impacts to the top of the head generate low PRA values (Rowson et al., 2012). In addition to distinguishing between PLA and PRA, it is therefore also important to consider impact direction in relation to TBI.

Head Impact Mechanisms in Rugby

Impact mechanisms, including duration and location, also predispose TBI severity (Greenwald & Ph, 2008). In rugby, the tackle is the most frequent contact event (Fuller, Brooks, Cancea, Hall, & Kemp, 2007), unsurprisingly causing most head injuries for men and women (King et al., 2019). One study attributed 49% of male head injuries and 52% of women's to the tackle (Cusimano et al., 2013), whilst a later study on men associated 64% of head injuries and 74% of concussions to tackle events (Roberts, Trewartha, England, Goodison, & Stokes, 2017). Of concussions sustained by men, 70% have been shown to be received by the tackler and 30% by the ball carrier (Cross et al., 2019).

The body part to which the head makes contact with also dictates TBI severity. Head-to-head collisions caused 10% of head injuries in men, and 7% in women, while head-to-knee produced 9% and 5% of head injuries, respectively (Cusimano et al., 2013). For elite males, video analysis revealed that 78% of HIA's were conducted following head-to-head contact, followed by head-to-elbow and, lastly, head-to-knee (Tucker et al., 2017). Preliminary findings in women's rugby suggest that head injuries are more frequently sustained from head-to-ground contact, rather than player-to-player contact as observed in the men (Day, 2020).

History and Development of Head Impact Telemetry Systems

Studies investigating SRC require an accurate method of identifying and quantifying HAE's above a given threshold. Early concussion models, including the Wayne State Tolerance Curve (WSTC; (Gurdjian, Roberts, & Thomas, 1966; Namjoshi et al., 2013), the Gadd Severity Index (GSI; Gadd, 1966) and Head Injury Criterion (HIC) (Hutchinson, Kaiser, & Lankarani, 1998) were greatly limited by failing to incorporate PRA, now recognised as a requirement of concussion (Kleiven, Peloso, & Von Holst, 2003). More complex injury metrics, combining PLA and PRA, have since been developed (Newman, Shewchenko, & Wlebourne, 2000), including the Rotational Injury Criterion and the Power Rotational Head Injury Criterion (Greybe et al., 2020).

The majority of HAE studies to date have used video analysis or inertial sensors, including accelerometers and gyroscopes (Bartsch, Samorezov, Benzel, Miele, & Brett, 2014; Camarillo, Shull, Mattson, Shultz, & Garza, 2013; Carey et al., 2019; King, Hecimovich, Clark, & Gissane, 2017). Most early research was conducted within helmeted sport, including ice hockey (Mihalik et al., 2012) and American football (Camarillo et al., 2013), as sensors embedded in helmets or mouthpieces were protected. Recently, other contact sports have used the xPatch, a skin-mounted sensor with accelerometer and gyroscope (Murayama, Hitosugi, Motozawa, Ogino, & Koyama, 2020), which has recorded mean PLA and PRA values of 15 *g* and 2,296 $rad \cdot s^{-2}$ in junior rugby (King, Hume, Gissane, & Clark, 2016). Detrimentally, soft tissue artifact and poor skull coupling during moderate impacts may result in skin-mounted sensors overestimating PLA and PRA, compared to the true movement of the underlying bone (Wu et al., 2016).

Lately, instrumented mouthguards (iMG) have enabled the unbiased identification and quantifying of head impacts (Greybe et al., 2020), in rugby (King et al., 2015), American football (Hernandez, Shull, & Camarillo, 2015), boxing and the martial arts (Hernandez et al., 2016). iMG have evolved from solely recording PLA (Greybe et al., 2020) to also recording PRA (Bartsch et al., 2014; Camarillo et al., 2013). The advantage of iMG during rugby games is that they comply with regulation 12, which prohibits clothing or skin-mounted sensors (World Rugby Handbook, 2019). Studies using iMG are emerging in women's rugby. During games, a median PLA and PRV of 32.16 *g* and 13.50 rad·sec^{-1} was recorded, compared to 29.38 *g* and 15.70 rad·sec^{-1} during training (Langevin et al., 2020). Additionally, over 12 games and three contact training sessions, a median PLA of 15.3 *g* and a change in rotational velocity of 5.5. rad·sec^{-1} was calculated (Kieffer, Vaillancourt, Brolinson, & Rowson, 2020). Compliance to concussion policies has been poor (Hollis et al., 2012), yet iMG technology adds another dimension to TBI detection and will improve knowledge on head injury biomechanics, force frequency and velocity in women's rugby (King, Hume, Gissane, Kieser, & Clark, 2018).

2.6 Head and Neck Anatomy

2.6.1 Anatomy of the Cervical Spine

The cervical region, located closest to the skulls base, is the first of five spinal regions (IGEA, 2020). The cervical spine has minimal curvature (Hedenstierna, 2008) and is formed of seven vertebrae (C1-C7), distinguished as the upper or lower cervical spine. The first vertebrae (C1), the Atlas, supports the skull and with the second vertebra (C2), the Axis, facilitates rotation of the head (IGEA, 2020). Between vertebrae, inter-vertebral discs reduce tension, shear and torsion (Yoganandan, Kumaresan, & Pintar, 2001). Spinal mobility is enabled between the eight motion segments of the cervical region (Nightingale et al., 2015) by articulations between adjacent vertebrae, intervertebral disc, facet joints (zygapophysial joints or z-joints) and ligaments containing a high collagen and elastin content to reduce tension (Mohan & Huynh, 2019). Combined, the tissues play a crucial role in maintaining the spines structure, by enabling and also limiting movement upon external loading, including trauma (Yoganandan et al., 2001).

2.6.2 Cervical Spine Sex Differences

The cervical spinal geometry of females is smaller, compared to the vertebral dimensions in size-matched males (Stemper et al., 2009). In females, the facet cartilage is thinner, the gap in cartilage cover larger (Yoganandan, Knowles, Maiman, & Pintar, 2003) and, whilst seated, neck curvature is less pronounced (Linder & Svedberg, 2019). The cervical spine influences the biomechanics of the neck. Females exhibit lower intervertebral coupling stability (Janssen, Drevelle, Humbert, Skalli, & Castelein, 2009), greater shear motion (Stemper, Yoganandan, & Pintar, 2004) and greater head-neck and spinal movements (Mohan & Huynh, 2019). Consequently, the load placed on the cervical spine and injury risk from soft-tissue deformation and tissue failure increases (Stemper et al., 2009). These factors explain females higher predisposition to whiplash, recorded during automotive rear impacts (Stemper et al., 2009).

Whilst limited studies have investigated females, research has shown they have lower load-bearing capacities of the cervical spines compared to their male counterparts, increasing the likelihood of vertebral fractures (Patel, Patel, Harrop, & Burger, 2014). During compressive drop tests to assess cervical spine failure loads (Nightingale et al., 1997), males withstood 2.24 ± 0.57 kN, compared to 1.06 ± 0.27 kN for females (Nightingale et al., 2015). A tolerance value of 1.68 kN was calculated for females, compared to 3.03 kN for males (Nightingale et al., 2015). Females cervical spines are less stable and proficient at resisting inertial loading and extreme spinal movements (Stemper et al., 2009), factors believed to contribute to females higher concussion prevalence (Mohan & Huynh, 2019).

2.6.3 Musculature of the Neck

Cervical spine musculature has properties unique to skeletal muscle and attach to the skull or vertebrae via short tendons. Fundamental for head and neck kinematics, cervical spine musculature allows for flexion (Flx), extension (Ext), lateral flexion and rotation (Siegmund, Winkelstein, Ivancic, Svensson, & Vasavada, 2009). The muscle fibre area is directly proportional to the force magnitude generated, with smaller muscles generally located close to the vertebral column and larger muscles superficially (Hedenstierna, 2008). Superficial muscles, the Trapezius (TZ), Sternocleidomastoid (SCM) and Levator Scapula have longer lever arms, producing great force. The TZ enables Ext, the SCM assists Ext, Flx and rotation (Hedenstierna, 2008). Four muscles located above the atlas (the suboccipital group) have short lever arms so are suited to providing head stabilisation (Hedenstierna, 2008). Posterior muscles include the Splenius, Semispinalis and Longissimus are vital for counteracting gravitational forces during neck stabilisation. Anterior muscles include the Longus Colli, Longus Capitis and Hyoid muscles enable head Flx but have smaller cross-sectional areas than posterior muscles. Consequently, neck Flx is weaker than Ext, with a peak force ratio for Flx: Ext calculated as 1:1.9 (Almosnino, Pelland, Pedlow, & Stevenson, 2009; Salmon et al., 2015). However, greater muscular endurance is recorded in flexor muscles opposed to extensor muscles, indicating that anterior muscle contains more type I muscle fibres than posterior muscles (Salmon et al., 2015).

Neck muscles influence cervical flexibility, rigidity and buckling behaviour (Nightingale et al., 2015). In response to an impact force, neck muscles work actively and passively to provide neck stabilisation and reduce acute muscular strain (Hedenstierna, 2008). However, the onset of muscle activation following an impact is unavoidably delayed by a 60-130 ms reaction time, dependent on impact severity, direction and additional stimuli (Hedenstierna, 2008). Muscular tensing prior to an impact is shown to increase neck stabilisation and decrease the force distributed to the neck (Chancey, Nightingale, Van Ee, Knaub, & Myers, 2003), reducing head deflection, ligament damage and cervical tissue damage during accidental injury (Brolin, Hedenstierna, Halldin, Bass, & Alem, 2008; Hedenstierna, 2008) (Brolin et al., 2008). Although amplified neck pain is reported from tensing during vehicle impacts (Jakobsson, Norin, & Isaksson-Hellman, 2000), subsequent studies confirm muscular activation is of major importance in decreasing cervical loading (Brolin et al., 2008).

2.6.4 Muscular Strength Sex Differences

Research consistently demonstrates that females have weaker neck muscles than males (Dick, 2009), by obtaining lower values in NS assessments (Suryanarayana & Kumar, 2005). Male NS has been recorded between 72-230N in Flx and 100-333N in Ext (Hedenstierna, 2008), whilst females obtained half the values of men (Peolsson, ÖBerg, & Hedlund, 2001). Whilst seated, peak directional NS were 72N and 41N for Flx, 100N and 72N for Ext and 76N and 54N for lateral flexion, for males and females, respectively

(Shrawan Kumar, Narayan, Amell, & Ferrari, 2002). Also whilst seated, NS in Flx is reported as 57N for males and 30N for females, in Ext 96N for males and 69N for females (Suryanarayana & Kumar, 2005). When correcting for head mass, maximal NS remained higher in males, with female NS in Flx representing 68% of male NS and 80% in Ext (Vasavada, Danaraj, & Siegmund, 2008). Assessments conducted in a simulated rugby contact posture also record greater NS for males than females (Salmon et al., 2015).

2.7 The Role of Neck Function in Contact Sports Injury Prevention

2.7.1 Cervical Spine and Neck Injuries

Reasons for Injury

The trauma that results in concussion is likely to simultaneously cause neck injury (Carmichael, Staton, Blatchford, & Stevens-Lapsley, 2019). In men's rugby, neck injuries are recorded at a rate of 6.1 and 10.8 per 1,000 player hours for youth and elite players respectively (Fuller, Brooks, & Kemp, 2007). Fuller et al. (2007) also reports an increased likelihood of obtaining subsequent neck injury following the first injury. Indeed, for females, in the 12-months following their latest concussion, greater head acceleration was recorded during simulated tackles (Bussey et al., 2019).

A large proportion of cervical spine injuries occur when the strength of the neck is unable to withstand the kinetic energy produced from the moving torso region (Nightingale et al., 2015). Previous research has only found a moderate correlation between neck circumference and neck strength (Catenaccio, 2017). Problematic for head weight stabilisation, however, is the delay in NS increases following the increase in head circumference during puberty (Carmichael et al., 2019). However, a high acceleration is not always required for brain injuries to occur, particularly during side impacts (Gennarelli et al., 2002). A head velocity of 3.05 $m \cdot sec^{-1}$ is considered great enough to cause cervical spine compression fractures, most commonly to the C5 vertebra (Nightingale et al., 2015). This equates to a fall height of 19.4 inches, meaning that many sports and daily activities come with a significant risk of neck injury (Nightingale et al., 2015). Furthermore, Chancey et al. (2003) proposed that the cervical spine can withstand compressive loads of 120 N when relaxed, and 1,400 N when tensed. Cervical injury following frontal inertial loading is highly influenced by cervical muscle properties, including the extent and timing of muscular activation, and the impacts inertia and orientation (Nightingale et al., 2015). Therefore, inter-study discrepancies may be due to, at least in part, their methodologies, including the participants, sport and hours of exposure.

The cause of sex-differences in cervical injury prevalence is relatively unknown. Disparities in head mass and neck stabilisation are said to predispose females to greater head accelerations during dynamic movements (R. Tierney et al., 2005). Additionally, weaker cervical musculature recorded in females explains why their linear acceleration (Mansell et al., 2005) and angular acceleration (R. Tierney et al., 2005) of the head and neck is greater. For females, this results in greater peak angular acceleration and displacement of the head, less effective absorption and dissipation of impact forces, and lower head-neck dynamic stabilisation, which together, increase the risk of cognitive impairment and concussion (R. Tierney et al., 2005). Concussion records therefore show that neck injuries, either in isolation or accompanied with SRC, are significantly more prevalent in females than males (Carmichael et al., 2019).

Frequent Injury Locations

High-impact loading to the head and neck can result in serious neurotrauma (Hedenstierna, 2008). During collision sports, this may be a direct impact or transfer of energy from accelerations (Hedenstierna, 2008). A Jefferson fracture to the atlas is the most common injury to the upper cervical spine (Jefferson, 1919). During contact sports, Hangman’s fractures could also occur from an impact to the face or chin (Levine & Edwards, 1985). In men’s rugby, fractures to the cervical spine have been suggested to most regularly occurred to the C4/5 and C5/6 motion segments due to cervical spine buckling (Kuster, Gibson, Abboud, & Drew, 2012). Conversely, Dennison, Macri, & Cripton (2012) argued that it is premature to disregard hyperflexion of the neck as a primary injury mechanism for male rugby players. No evidence exists to suggest this is the same for female players.

In order to investigate the necks response to injury, cadavers have been used. One study replicating horizontal athletic neck injuries recorded series injuries in many levels of the cervical spine (Ivancic, 2012). Specifically, using load cells, Ivancic (2012) demonstrated that each vertebra experienced a small inertial force, whereas the necks reaction was greater. During free-fall drop tests on eight cadavers from 0.8-1.8m, head impact forces between 3.2 and 10.8 kN were reported (Nusholtz, Huelke, Lux, & Alem, 1983). Cadavers are limited by their absence of muscle, thus real head and neck movement is not accurately represented in cadaver studies (Nightingale et al., 2015). However, all cadaver studies successfully demonstrate the great influence that the inertial orientation of the spine has on injury outcome (Nightingale et al., 2015).

2.7.2 Neck Strength and Endurance Assessments

NS and NE can be measured either dynamically, or statically using isometric contractions. The advantage of isometric assessments are that they reduce the risk of injury and mimic the postural role of the muscle (Salmon, 2014). Obtaining reliable isometric NS and NE measurements is challenging due to methodological and equipment limitations (Dvir & Prushansky, 2008). NS assessments are necessary as anthropometric measurements, such as height, body mass, body mass index (BMI) and neck circumference, have been recorded to only modestly correlate with neck strength (Catenaccio, 2017). These limited correlations are more prominent in females, as sexual dimorphism affects body fat and muscle mass distribution (Catenaccio, 2017). Past studies have frequently measured isometric NS using hand-held dynamometers (Mihalik et al., 2012), yet low reliability associated with hand-held devices has instigated a change to fixed frame dynamometry (Hall et al., 2017).

The protocol previously used to obtain neck extensor endurance required the participant, in prone with their neck unsupported, to hold a weight plate attached to their head using a Velcro band, in a fixed position off the ground (Ljungquist, Harms-Ringdahl, Nygren, & Jensen, 1999). Once more, assessments of neck flexor endurance necessitated development, conducted in supine, the protocol used the examiners hand to detect a reduction in head flexion (Harris et al., 2005). Past research, including studies less applicable to the general population having been conducted on participants experiencing neck pain (Edmondston et al., 2008), have raised concerns for participant safety due to their potential to instigate cervical injury.

A range of testing positions have been optimised, including standing, seated, prone and supine (Salmon et al., 2015). The optimum assessment position for rugby players is in the horizontal plane, as in this position during tackles, scrums and rucks, a significant load is place on the cervical spine (Swain, Pollard, & Bonello, 2010). Thus, Salmon et al. (2015) constructed an apparatus which positioned the neck horizontally in a simulated rugby contact posture, to place the participants under similar demands. Across three sessions, Flx and Ext were assessed through a single maximal voluntary contraction (MVC) and a NE trial (Salmon et al., 2015). The research by Salmon et al. (2015) had improved relevance to studies which chose a seated (Hamilton et al., 2012; Oliver & Du Toit, 2008) or standing position (Strimpakos, Sakellari, Gioftsos, & Oldham, 2004).

Instrumental and procedural discrepancies, however, still largely contribute to varying intrarater and interrater reliability between studies (Hall et al., 2017). This includes differing testing positions, inclusion of warm-up exercises, MVC duration and repetitions, the number of researchers collecting data and the use of motivational strategies. Commercially available, custom built NS testing apparatus are therefore favoured in research to improve standardisation of testing. Adjustable straps are reported to be an important design feature on fixed-frame devices (Hall et al., 2017). These secure the participant and immobilise the torso, to ensure that each measurement is a true representation of only the necks isometric contraction (Hall et al., 2017).

2.7.3 Neck Strengthening Training Programmes

The attention of researchers has been drawn towards NSTP's, due to the association between injury to the head and neck and concussion (Hamlin, Deuchrass, Elliot, Raj, & Promkeaw, 2020). Previous research shows great variation in the duration and methods of NS training, as well as the extent to which they provide positive outcomes (Hamlin et al., 2020; Naish, Burnett, Burrows, Andrews, & Appleby, 2013). Retrospective analysis by Naish et al. (2013) of a progressive, 26-week programme for professional male rugby players found a significant decrease in cervical spine injuries, following isometric neck strengthening exercises and isometric cable holds (Naish et al., 2013). Recently, a six-week programme of daily NS exercises in Flx, Ext and lateral flexion, using a weighted head harness, resulted in significant improvements in isometric strength in Ext and lateral flexion for amateur male rugby players (Hamlin et al., 2020). For females, resistance training has successfully alleviated neck pain, improved mobility and NS in office workers (Li et al., 2017). Once more, rugby-specific studies conducted on female cohorts are scarce and require further investigation.

2.7.4 Benefits of Neck Strengthening

Muscular and ligament involvement in NSTP's (Falla, 2004) has shown effective at reducing neck Flx and Ext (Nightingale et al., 2015), improving neck stability and decreasing neck injury following inertial loading of the head (Hrysomallis, 2016; Oliver & Du Toit, 2008). Furthermore, a reduction in head impact magnitude and concussion have been reported (Collins et al., 2014), particularly in contact sports (Dezman, Ledet, & Kerr, 2013; Naish, Burnett, Burrows, Andrews, & Appleby, 2013; Quarrie, Cantu, & Chalmers, 2002). The beneficial effect of NSTP's is that the cervical musculature can greater absorb and control biomechanical forces transmitted to the cervical region, influencing head kinematics (Salmon et al., 2015). On this basis, improving the NS of women's rugby players is paramount, considering their high incidence of head injuries (Kemp et al., 2018). It is evident that NSTP's are easy to implement and highly beneficial, with Collins et al. (2014) reporting that only a one-pound increase in NS is required to decrease concussion risk by five percent. It is pertinent to note; however, that contradictory evidence does exist. Specifically, Eckersley, Nightingale, Luck, & Bass (2019) found that improving NS did not affect head kinematics in the short-term during simulated athletic impacts. Therefore, the effect of a NSTP on NS and NE are investigated in the present thesis, on the recommendation that NSTP's be integrated into strength and conditioning programmes in women's rugby as a principal mechanism for concussion prevention (Collins et al., 2014).

Chapter 3: Methods

3.1 Experimental Design and Methodological Overview

A total of 30 volunteers (20.4 ± 2.3 yrs.) from two United Kingdom-based, university first XV women's rugby teams participated in this longitudinal, intervention study (Team 1: *n*=20; Team 2: *n*=10). All participants were assigned the biological sex of female at birth. The relationships between isometric neck strength (NS) and strength endurance (NE), anthropometrics, playing position, playing experience and level, and on-field head acceleration event (HAE) mechanisms were investigated. All data were collected over the 2019/2020 British Universities College Sports (BUCS) season and all matches were played on outdoor, grass pitches.

For all players (*n*=30), baseline testing involved the measurement of NS, NE, and anthropometric variables. These variables were body height, body mass, head circumference, neck circumference and shoulder breadth. For each participant, playing position, experience and level were recorded at this time. The intervention group (Team 1 players only; *n*=20) then participated in a nine-week neck strengthening training programme. NS and NE re-tests were conducted for these players at mid-season, to assess the efficacy of the intervention at its half-way point. The planned continuation of this intervention for Team 1 players for a further eight weeks was not feasible due to the COVID-enforced premature end to the rugby season. This also applied to planned post-season retests for NS, NE and anthropometric data for all players which did not take place. From the intervention group, 12 players (Forwards *n*=4, Backs *n*=8) were fitted with bespoke instrumented mouthguards (iMG, Protecht™, Sport and Wellbeing Analytics Ltd, Swansea, United Kingdom) to measure the magnitudes of HAE's experienced during six competitive games. Video footage of games was recorded to correlate mouthguard data with HAE mechanisms.

3.2 Participants

Both teams competed in the 2019/20 BUCS Premier South league with comparable standards of play. Players were classified by position as either forwards (Fwds) or backs (Bks). Players were also graded by playing experience (the number of years of competitive rugby participation) and rugby playing level; either 'university-level', or ‘higher-level’ if participants also competed at regional (Reg), premiership (Prem) or national (Nat) level competitions at the time of the study. A summary of these data is given in Table 3.1.

Table 3.1: Participant descriptive and playing characteristics for all players and for the intervention group only, separated into forwards and backs

		Age (years)	**Playing experience (years)**	**Playing level**			
	n	Mean ± SD	Mean ± SD	Uni/Club	Reg.	Prem.	Nat.
All	30	20.4 ± 2.3	5.5 ± 3.7	17	8	2	3
Forwards	14	20.5 ± 1.9	6.4 ± 3.7	7	3	2	2
Backs	16	20.4 ± 2.6	4.8 ± 3.7	10	5	0	1
Intervention Group	20	20.7 ± 2.1	5.1 ± 3.6	13	3	1	3
Forwards	9	21.2 ± 1.9	5.3 ± 2.8	6	0	1	2
Backs	11	20.3 ± 2.2	4.9 ± 4.3	7	3	0	1

Prior to the commencement of the study, the purpose and requirements were explained to all prospective participants via a PowerPoint presentation and a participant information sheet (Appendix A). Players who volunteered to participate then provided written informed consent (Appendix B). Approval was also granted from each team’s coaching staff before the commencement of the study. Inclusion criteria required participants to be current, active members of a women’s university first XV rugby team, with no injuries affecting rugby activities. Prior to inclusion, each participant completed a medical history questionnaire (Appendix C) and a physical activity readiness questionnaire (PAR-Q). Participants who reported neck injuries over the previous year were excluded from the study. Participants who experienced a high magnitude impact or any neck pain during the intervention followed medical advice regarding returning to training and competition. Appropriate ethics approval was granted by Swansea University Research Ethics Committee (ref no: 2016-059) and the study was conducted in accord with the Declaration of Helsinki.

3.3 Anthropometric Testing

3.3.1 Measurements and Materials

The variables in Table 3.2 were measured for each participant at baseline using stated equipment. Each measurement was repeated three times and a mean calculated. Body mass index (BMI) and neck-to-head circumference ratio (N:H) were also calculated from these data.

Table 3.2: Anthropometric measurements taken from each participant

Measurement	Units	Acronym	Resolution	Equipment
Standing Height	cm	SH	Closest 1 mm	Seca Portable Stadiometer 225
Body Mass	kg	BM	Nearest 0.1 kg	Seca digital scales 770
Shoulder Breadth	cm	SB	Nearest 5 mm	Large bone callipers
Head Circ.	cm	HC	Nearest 1 mm	Anthropometric tape measure
Neck Circ.	cm	NC	Nearest 1mm	Anthropometric tape measure

All anthropometric measurement methods were consistent with the International Society for the Advancement of Kinanthropmetry (ISAK) standards (R. Wood, 2008). These standardised protocols for locating body landmarks and taking measurements were followed to avoid subjectivity and increase precision, reliability and repeatability. For each variable, the same researcher measured all participants, and each measurement was taken three times.

3.3.2 Anthropometric Testing Protocols

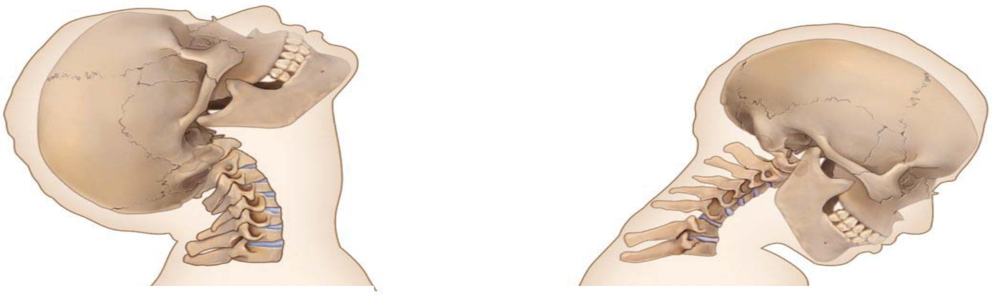
For standing height (SH), the participant stood in an upright position with their shoes removed, feet together and arms by their side. The participant's upper back and heels were in contact with the stadiometer (Wood, 2008). Whilst looking straight ahead the participant was asked to inhale as the measurement plate was lowered. Once touching the top of their head, the participant exhaled and stood tall to their full height. Body mass (BM) was measured with the participants excess clothing and shoes removed. The participant was instructed to stand and remain still in the centre of the scales, with their arms by their side (Wood, 2008).

For HC, NC and SB, the participant was seated in a straight-backed chair. To obtain HC, the tape measure was encircled around the widest part of the skull, immediately above the eyebrow line. The tape measure was held at a horizontal level, above the ears with hair compressed (Wood, 2008). To measure NC, the participant was requested to hold their head in an upright position and look straight ahead. The tape measure, lying flat to the skin, was positioned level around the neck, superior to the thyroid cartilage (Norton, 2019). To record SB, the participant sat upright and the acromion process was located (Wood, 2008). The arms of the callipers were positioned on the lateral borders of this landmark and the distance between measured.

3.4 Isometric Neck Strength and Neck Strength Endurance Assessments

3.4.1 Isometric Neck Strength Testing Apparatus (INSTA)

A purpose-built isometric neck strength testing apparatus (INSTA, Figure 3.2) was used to measure maximal isometric NS and NE. Flexion (Flx), extension (Ext), left lateral flexion (L-Flx) and right lateral flexion (R-Flx) were included in all NS and NE tests (Figure 3.1). Previous methods of NS assessment have adopted seated or supine positions (Salmon et al., 2015). These methodologies can lack the robustness, applicability and repeatability required for elite contact sport athletes (Fuller, Brooks, & Kemp, 2007; Swain et al., 2010). Salmon et al., (2015) designed a NS testing apparatus to measure maximal voluntary contraction (MVC), which was adapted for the current study, where the participant was prone, with their head in neutral, in a simulated scrum position (Figure 3.2). Previous studies have reported excellent reliability using the same equipment and quadruped testing position (Mcbride & Oxford, 2020).



Extension Flexion

Left lateral flexion Right lateral flexion

Figure 3.1: Movements of the cervical spine (https://learnmuscles.com/glossary/cervical-spine-ranges-of-motion-rom/

The INSTA measured force (N) using a fixed frame dynamometry arrangement of four inward-facing 50 to 150 kg capacity load cells (Tedea-Huntleigh, Vishay Measurements Group, Hampshire, U.K.). These were set to measure at a sampling frequency of 200 Hz. The participant's head was required to be centrally located and not in contact with any load cell when in a neutral position. Two load cells measuring Flx and Ext were positioned below and above the head, respectively, with the bottom load cell inferior to the supraorbital ridge, the top load cell above the external occipital protuberance. Measurements in flexion involved movement of the head forwards, with the participants chin moving towards their chest. For extension, the head moved backwards, and the participants chin away from their chest (Figure 3.1; Kent, 2006). Two load cells measuring L-Flx and R-Flx positioned either side of the head, above the eternal auditory canals, directly superior to the ears (Figure 3.2). Measurements in left and right lateral flexion required movement of the head towards the left or right shoulder respectively (Figure 3.1; Kent, 2006). The positions of the load cells were adjustable, accommodating different head dimensions. Data were recorded on a connected computer using Hauch and Bach DOP4 software (Lynge, Denmark).

The design of the INSTA included a padded chest bench to maintain a standardised body position (Salmon et al., 2015). The trunk region was restricted using a 4-point harness and leg straps prevented leg movement and torsion of the torso during lateral tests (Edmondston et al., 2008). This intentionally compromised the functionality and sports specificity of the testing position, to make measurements more repeatable and a true representation of only the necks isometric contraction (Hall et al., 2017). Kneeling on a cushioned pad alleviated muscular strain on the lower back and ensured the participant's back level was horizontal, with their hips at a right angle. The participant's knee height could be raised using weight plates and a padded cushion, with alterations being recorded to ensure consistency between trials. The participant was requested to place their arms behind their back and cross over their lower legs to prevent recruitment of accessory muscles during testing. Taken together, the design limited use of synergistic muscles, only enabling the recruitment of neck musculature (Oliver & Du Toit, 2008).

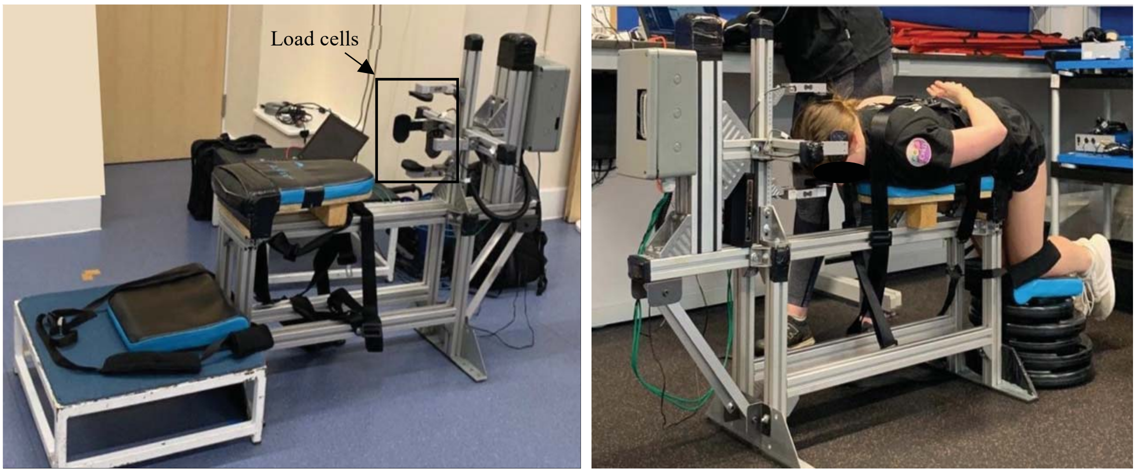


Figure 3.2: Photographs showing the isometric neck strength testing apparatus (INSTA) (left) and a participant demonstrating the testing position with their head in a neutral position (right)

3.4.2 Pilot Study

The methodology for the pilot study is outlined in Table 3.3. The trials enabled refinements to be made to the testing procedure. During the pilot study, fatigue compromised maximal isometric NS data when collected over six seconds. Reducing the time to three seconds was found to be adequate time for the participants to gradually achieve their MVC without fatigue. Secondly, the pilot study collected unreliable data for head mass in both prone and supine positions which were to be used to account for head mass during Flx (Salmon et al., 2015). The participant could not maintain a steady recording over 10 seconds when resting their head on the load cell used to record Flx. Instead, calculations of relative mass were concluded to be more accurate. Thirdly, a significant learning effect was evident, with greater maximal isometric NS values during repeat tests in each direction compared to the first attempt. Therefore, a familiarisation protocol was added to the final testing procedure to control for familiarisation being a reason for MVC improvements following the intervention.

Table 3.3: Pilot study testing procedure for the neck strength (NS) and neck strength endurance (NE) trials

	Force Output (% of MVC)	**Duration of Force Output**	**Direction of Force Output**	**Tests per Direction**	**Rest (seconds)**
NS	100	6 seconds	Flx, Ext, L-Flx, R-Flx	3	20 between repetitions 60 between directions
NE	70	Until fatigue or output <70% for 3 seconds	Flx, Ext, L-Flx, R-Flx	1	120 between directions

3.4.3 Finalised Testing Procedures

Both baseline and mid-season data were collected in a strength and conditioning training facility. Each participant completed a warm-up, NS trial (including a familiarisation protocol) and NE trial (with familiarisation protocol) on the same day. The NS protocol always occurred prior to the NE protocol but, within each protocol, the direction of effort was randomised. Both baseline and mid-season data collection were completed for all participants within a four-week period on non-consecutive days.

During data collection, positive competency feedback and motivational strategies were implemented to reduce the negative influence of psychological factors, increase motor neurone recruitment and increase peak force during MVCs (Belkhiria, De Marco, & Driss, 2018; Binboga, Tok, Catikkas, Guven, & Dane, 2013; Jung & Hallbeck, 2004). The same researchers collected all of the data, enabling consistent implementation of strategies between all participants and between baseline and mid-season timepoints.

Warm Up

All participants completed the standardised warm up in Table 3.4 prior to data collection, modified from previous studies (Salmon et al., 2015). Activation of the neck and upper back muscles was the primary area of focus. Following a five-minute ergometer row, four exercise were completed in turn, each for three sets of ten repetitions. Lastly, deep neck flexor isometric protractions, repeated three times in both prone and supine, required the participant to tuck in their chin, raise their head five centimetres off the ground and hold it elevated for ten seconds.

Table 3.4: Protocol description for the warm-up

Exercise	**Sets and Repetitions/ Duration**
Rowing ergometer	5 minutes
Shoulder shrugs	3*10
Protractions and retractions	3*10
Circumduction's	3*10
Semi-head rolls	3*10
Deep neck flexor isometric protraction holds (prone)	3*10 seconds
Deep neck flexor isometric protraction holds (supine)	3*10 seconds

Maximal Isometric Neck Strength Testing

Before data collection, participants completed a familiarisation protocol consisting of unrecorded force application for three seconds at 25%, 50% and 75% effort in each direction, with 20 seconds rest between each. For the NS trial, the INSTA was used to record the participants three-second MVC of absolute NS in Flx, Ext, L-Flx and R-Flx, three times in each direction. This protocol enabled several measurements of NS to be obtained quickly, reducing the time required in the INSTA for each participant. To avoid injury, the participants were encouraged to reach their MVC progressively, rather than upon initial contact with the load cell. A rest interval of 20 seconds between each repetition allowed the participant to reset into the neutral position. Between each direction, a rest interval of 60 seconds was given, consistent with what was deemed sufficient in the procedure developed by Salmon et al. (2015). The participant's MVC for each direction was the highest value achieved in any one of the three directional tests. Relative MVC was calculated by dividing average absolute MVC (N) by body weight (N).

Isometric Neck Strength Endurance Testing

Following completion of the NS testing, participants were unstrapped from the apparatus and given 20 minutes recovery before the NE trial. Once strapped back into the apparatus, participants were familiarised with the NE trial procedure. This required the submaximal target force of 70% of their MVC to be maintained for as long as possible, once in each direction. To sustain the required force, visual graphical output on a computer screen and verbal feedback were provided. At the point where the output decreased to less than 70% of the target force for three seconds, the test was stopped. This was recorded as the time to fatigue (TTF). A rest interval of two minutes was given between each direction. NE was the time (seconds, s) that each participant could sustain 70% of their absolute MVC. All NE data was collected at baseline.

3.5 The Neck Strengthening Training Programme Intervention

The intervention group (Team 1 only) undertook the neck strength training twice per week, on the same days at a consistent time, as part of a revised strength and conditioning programme. A maximum of two exercises were completed per training session, requiring 10 minutes. The training intervention was composed of exercises previously reported to increase isometric NS (Barrett et al., 2015; Hanney & Kolber, 2007; Kevin & Brian, 2014; Naish et al., 2013; Salmon et al., 2015). To be appropriate for the women's team, the intensity of exercise and time for which each activity was undertaken were carefully considered. The training intervention was supervised by the primary researcher and a strength and conditioning coach to ensure correct technique. When away from university, the training was supervised remotely, using demonstration videos and virtual guidance. Each participant's compliance to the intervention was classified as either 'high-compliance' or 'low-compliance' according to their attendance record to training.

The training intervention structure was founded on the theory of progressive overload (Middleton, Govus, & Clarke, 2019). It was not uncommon for participants to be at different stages of the programme on different weeks, as progression was dependent on the individual's competency at each exercise. An example of one participant's training programme is outlined in Table 3.5. Following baseline NS testing, the first part of the intervention was then implemented over nine weeks (including three-weeks of remote supervision away from university). Following this, mid-season NS data was measured. The second part of the intervention then commenced, with a planned duration of eight weeks. This was cut short after two weeks, when the rugby season came to a premature end due to the COVID-19 pandemic. Post-season NS data could therefore not be obtained. The COVID-19 pandemic meant that having collected baseline NS data from all players (Team 1 and Team 2), post-season NS data could not be compared between the intervention group (Team 1) and the team of comparable standard who did not undertake the intervention (Team 2).

Table 3.5: Exemplar neck strengthening training programme for one participant

Week	Stage	Training Exercise (2 sessions per week)	Hold Duration (sec)	Repetitions per Session
1-4		Pre-Season Assessment Period		
5	1	Supine on bench with incline	10	10
6	2	Supine on bench	15	15
7	3	Prone on bench	10	10
8	3	Prone on bench	15	15
9	4	Supine & Prone on bench	10, 10	10, 10
10	4	Supine and Prone on bench	15, 15	10, 10
11	5	Resistance band/ Exercise ball	-	3 (Flx, Ext, L-Flx, R-Flx)
12	5	Resistance band/ Exercise ball	-	3 (Flx, Ext, L-Flx, R-Flx)
13	5	Resistance band/ Exercise ball	-	3 (Flx, Ext, L-Flx, R-Flx)
14-17		Mid-Season Assessment Period		
18	4	Supine & Prone on bench	10, 10	10, 10
19	4	Supine & Prone on bench	15, 15	10, 10
20	5	Resistance bands	-	3 (Flx, Ext, L-Flx, R-Flx)
21	5	Resistance bands	-	3 (Flx, Ext, L-Flx, R-Flx)
22	5	Resistance bands	-	5 (Flx, Ext, L-Flx, R-Flx)
23	5	Resistance bands	-	5 (Flx, Ext, L-Flx, R-Flx)
24	6	Training harness	-	3 (Flx, Ext, L-Flx, R-Flx)
25	6	Training harness	-	5 (Flx, Ext, L-Flx, R-Flx)
26-29		Post-Season Assessment Period		

3.6 Head Acceleration Event Data

3.6.1 Protecht™ Head Impact Telemetry System

The Protecht™ telemetry system measures tri-axial linear head acceleration and rotational velocity during head acceleration events (HAE; both direct head impacts and indirect body impacts). Resultant peak linear acceleration (PLA, measured in *g*) and resultant peak rotational acceleration (PRA, measured in $rad \cdot s^{-2}$) were calculated from the iMG time series data in real time. Time-stamped digital video footage was recorded for all competitive games to verify iMG data and characterise HAE mechanisms with corresponding impact magnitudes. Footage was collected from three sideline cameras on tripods, positioned to ensure a view of all angles of the pitch. Where possible, professional footage was obtained which was generally filmed from the halfway line.

The iMG's were made bespoke for each of the 12 participants to whom they were provided, using the participant's dental impressions. This was to ensure secure sensor-skull coupling directly to the upper dentition, to prevent soft tissue artefact affecting the accuracy of HAE data (Kuo et al., 2016). From the dental impressions deemed suitable for iMG production, and due to miscommunication with the manufactures, this resulted in the uneven distribution of forward and back players with iMG’s.

The iMG system contains an embedded 9-axis inertial measurement unit (IMU) and an additional triaxial accelerometer (LSM9DS1 and H3LIS331DL, respectively, ST Microelectronics, Genova, Switzerland). The iMG samples over a 104 ms period at 1,000 Hz (linear accelerometer) and 952 Hz (gyroscope, measuring rotational velocity), with a 16-bit resolution and ranges of ± 200 *g* and ± 35 rad·s^{-1}, respectively (Greybe et al., 2020; Liu et al., 2020). The raw data is then transmitted via radio frequency to a computer and stored as a time-series CSV file. The system also contains a proximity sensor to ensure accelerations are only recorded when the guard is coupled to the participant's teeth.

3.6.2 Head Acceleration Event Data Processing

Time series data from the iMG system (Figure 3.3) were downloaded as raw data files and post-processing was undertaken outside of the iMG system. All data were filtered using a 4th order, zero lag, low-pass Butterworth filter, with impact-specific, optimal cut-off frequencies determined through residual analysis, performed by a project supervisor. Filtering was applied to vector component and scalar magnitude data. Rotational velocity data was differentiated using 5-points to calculate rotational acceleration. Where PLA values dropped below 9.6 *g* post-filtering, these were excluded. This was deemed normal for natural movements, such as jumping, during contact sports participation, which do not typically exceed this magnitude (Ng, Bussone, & Duma, 2006).

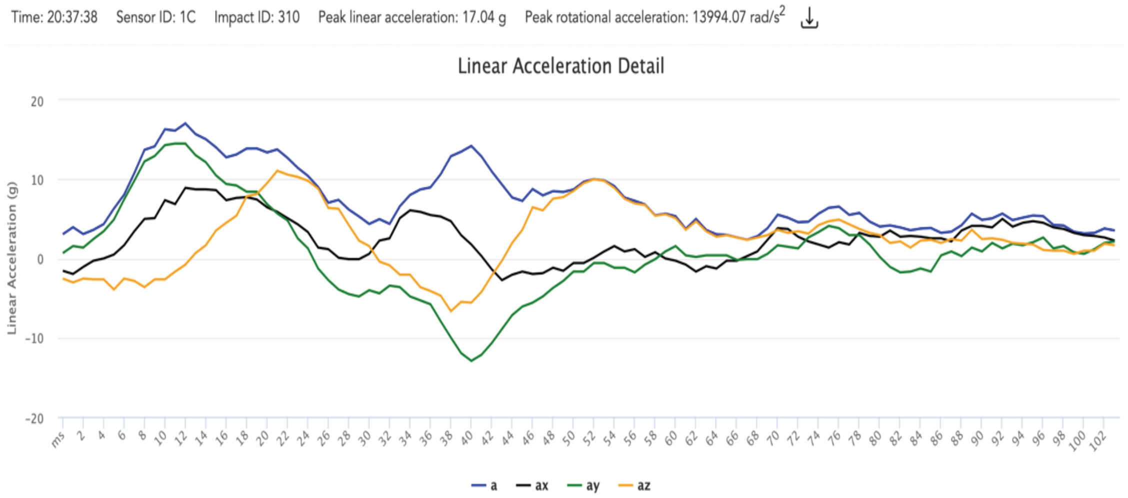


Figure 3.3: Unfiltered vector and resultant linear acceleration time-series data for one head acceleration event (HAE) *Protecht®*

3.6.3 Head Acceleration Event Verification

All HAE data underwent both video and waveform verification procedures to identify true and false positive impacts. Firstly, impacts were legitimised by cross-referencing the video footage with the iMG data. Impact verification was conducted by pairing the time on the video at which the impact was sustained with the iMG systems GMT time at which the impact was detected. The impacts were filtered to ensure that each impact recorded by the iMG system corresponded with an acceleration causing event on the video footage.

For all video verified HAE's, stage two of verification involved an assessment of the HAE timeseries waveforms (Figures 3.3 and 3.4). A legitimate waveform reflective of a realistic human head movement must have a smooth bell-shaped curve (Figure 3.3). Waveforms caused by shouting, biting or insertion/removal of iMG display sharp peaks, unrepresentative of human head acceleration profiles (Figure 3.4). Impacts with these distinct profiles were excluded from the dataset, along with any incomplete waveforms, where data had been dropped during transmission.

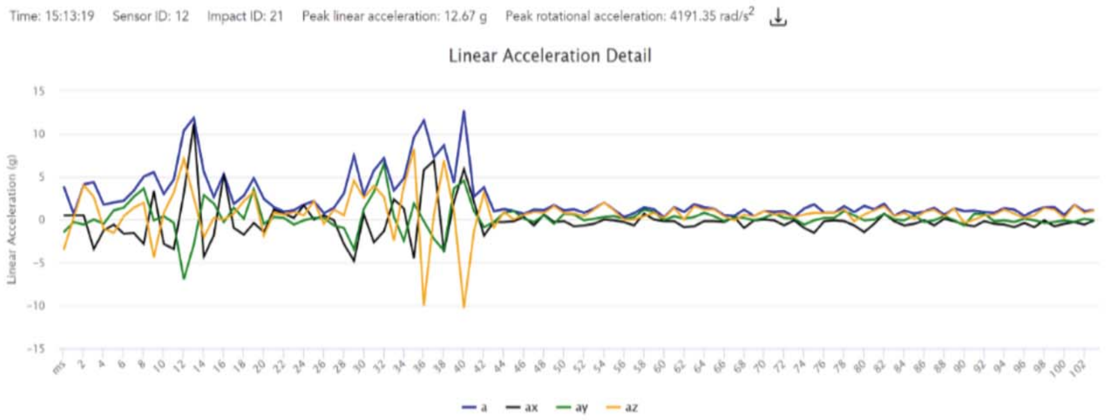


Figure 3.4: Unfiltered vector and resultant linear acceleration graph for one bite Protecht®

Video footage was also used to identify the causative mechanisms of each HAE (Table 3.6). Impacts were classified according to the direction of head movement, game event, head action and game event phase.

Table 3.6: Classification categories for head acceleration event (HAE) mechanisms

Head Acceleration Event Mechanism	Classification Categories
Direction of Head Movement	1. Backward Extension 2. Forward Flexion 3. Right Lateral Flexion 4. Left Lateral Flexion
Game Event	1. Tackle as tackler 2. Tackle as ball carrier 3. Ruck 4. Maul 5. Lineout 6. Scrum
Head Action	1. Indirect impact to head 2. Direct head impact on soft body part 3. Direct head impact on hard body part 4. Head to ground 5. Other
Game Event Phase	1. Stood on feet/ supporting body weight 2. During the fall/ feet not in full contact with ground 3. Lying on ground

Note. **Direction** refers to the direction in which the head travels during the head acceleration event. **Game Event** refers to the in-game event during which the head acceleration event occurred. **Head Action** describes the physical head dynamics during the head acceleration event, and **Game Event Phase** refers to the phase within the game event (e.g., tackle, ruck, maul, lineout, scrum) in which the head acceleration event occurred.

3.7 Statistical Analysis

Data analysis was conducted using Microsoft Excel (Version 365) and IBM SPSS Statistics for Windows (Version 26; IBM Corp). All data were tested for normal distribution using Shapiro Wilk tests (Shapiro & Wilk, 1965), with skewness and kurtosis values (Cramer & Howitt, 2004) and visual examination of histograms also referred to. Parametric and non-parametric tests were subsequently used as appropriate for normal and non-normally distributed data, respectively. The analysis was comprised of: Independent t-tests or non-parametric Mann Whitney U tests, to compare between two independent groups of participants, such as between forwards and backs. Non-parametric, Kruskal Wallis tests were used to investigate the significance of several independent variables at once, such as the classification categories for each HAE mechanism. Paired sample t-tests or non-parametric Wilcoxon Signed Rank tests were conducted to compare two experimental conditions where the same participants took part in both, such as the intervention group at baseline and mid-season. Correlations were used to measure the relationship between two continuous variables, such as HAE magnitude and NS. Two-way multivariate analysis of variance (MANOVAs) were conducted to test several, continuous dependent variables simultaneously, across two independent variables, such as the effect of playing level and playing position on absolute NS and relative NS.

Data was reported as the coefficient of determination reported (R^2) and probability (*p*) values. Fundamentally, R^2 measures the proportion of variation in the dependent variable that can be attributed to the independent variable, between 0 (no association) and 1 (perfect association). Whereas *p* values measure how likely it was that any observed correlation was due to chance, between 0 (0% due to chance) and 1 (100% due to chance).

Baseline anthropometric and neck strength tests were conducted on all players and separately for the intervention group (Team 1). Had the collection of post-season data been feasible, all baseline anthropometric and neck strength tests would have been repeated post-season, for all players and separately for both the intervention group (Team 1) and Team 2.

3.7.1 Baseline Anthropometric Variables and Neck Strength

Independent t-tests or Mann-Whitney U tests were conducted to determine the influence of playing position on baseline anthropometric variables, neck strength, neck strength endurance, neck strength imbalances between Flx and Ext (Flx - Ext) and between L-Flx and R-Flx (L-Flx – R-Flx). The relationships between key anthropometric variables were assessed using Spearman's correlations. Relationships between anthropometric variables and neck strength, neck strength endurance, neck strength imbalances between Flx and Ext and between L-Flx and R-Flx were assessed using Spearman's rho or Pearson's correlations. Neck strength and neck strength endurance in the anteroposterior direction (flexion combined with extension, Flx + Ext) was compared to the mediolateral direction (left lateral flexion combined with right lateral flexion, L-Flx + R-Flx), for imbalances between directions, using Wilcoxon signed rank tests or paired samples t-tests.

MANOVAs were conducted to investigate the main effect of playing level (university-level or higher-level) and playing position, as well as the interaction effect of both parameters on neck strength, neck strength imbalances between Flx and Ext and between

L-Flx and R-Flx. Spearman's rho correlated rugby playing experience (years) with neck strength, neck strength endurance and neck strength imbalances between both Flx and Ext and L-Flx and R-Flx.

3.7.2 Intervention Effect on Neck Strength

A paired samples t-test was used to assess the efficacy of the neck strengthening programme, comparing the intervention groups neck strength at baseline and at mid-season. Only participants who remained committed to the intervention and who had attended both baseline and mid-season neck strength assessments were included. Independent t-tests compared Team 2's baseline neck strength with the neck strength of the intervention group at baseline. Independent t-tests or Mann-Whitney U tests were conducted to determine the influence of playing position on mid-season neck strength, neck strength imbalances between Flx and Ext and between L-Flx and R-Flx. Paired samples t-tests investigated the effect of the neck strengthening programme on the intervention groups directional and positional mid-season neck strength.

Mid-season neck strength in the anteroposterior direction was compared to the mediolateral direction, using Wilcoxon signed rank tests. Independent t-tests were conducted to determine the influence of playing level and compliance level (high-compliance or low-compliance) on mid-season neck strength. MANOVAs were conducted to investigate the main and interaction effect of playing level and position on mid-season neck strength, neck strength imbalances between Flx and Ext and between L-Flx and R-Flx. Spearman's rho correlated playing experience with mid-season neck strength and neck strength imbalances between both Flx and Ext and L-Flx and R-Flx.

3.7.3 Head Acceleration Event Telemetry Data

HAE magnitude data for the intervention groups iMG wearing players consisted of PLA and PRA, which were analysed independently. The influence of HAE mechanisms on magnitude were investigated, using Kruskal Wallis tests. HAE magnitude was investigated according to playing position and playing level using Mann Whitney U tests, and in relation to playing experience, anthropometric variables and time in play per game using Spearman's Rho. HAE magnitude was compared between HAE's recorded during the first half and second half of the season using Mann Whitney U tests.

3.7.4 Integrated Analysis

For each participant from the intervention group wearing an iMG, mean PLA and PRA calculated for the first half and second half of the season were compared with the participants corresponding baseline or mid-season neck strength, using Pearson's correlations. For all 73 HAE's recorded, the PLA and PRA were compared with the corresponding baseline or mid-season neck strength and neck strength endurance of the participant who sustained the HAE, using Spearman's rho.

The magnitude of HAE's, classified by direction of head movement, were compared against the corresponding and opposing directional neck strength and neck strength endurance. Flx and Ext combined and L-Flx and R-Flx combined were also compared with HAE magnitude. Analysis was separated into HAE's recorded during the first and second half of the season and baseline and mid-season neck strength.

Mann-Whitney U compared the HAE magnitude of all HAE's between neck strengthening intervention compliance groups. Each player's average HAE magnitude for the whole season and separated into the season's first and second half were compared between compliance groups, using independent t-tests. Spearman's Rho compared the neck strengthening intervention week number with the magnitude of all HAE's during the whole season.

Chapter 4: Results

4.1 Baseline Anthropometric Variables According to Playing Position

The baseline anthropometrics for all players are shown in Table 4.1, with biological age, playing age and playing level shown in Table 3.1. Independent t-tests revealed forwards had significantly greater body mass and BMI than backs ($p \leq 0.05$), but no other differences were found for standing height, neck circumference, head circumference, shoulder breadth or neck-to-head ratio ($p > 0.05$). For the intervention group (Team 1) independently, BMI, neck circumference, shoulder breadth and neck-to-head ratio were significantly greater in the forwards than backs ($p \leq 0.05$), but no significant differences were found for body mass, standing height or head circumference ($p > 0.05$).

For all players, strong positive Spearman's correlations were found between neck circumference and body mass ($r_s = (26) = 0.73$, $p \leq 0.01$) and between neck circumference and shoulder breadth ($r_s = (27) = 0.75$, $p \leq 0.01$). For the intervention group separately, strong positive Spearman's correlations were found between neck circumference and body mass ($r_s = (17) = 0.73$, $p \leq 0.01$) and between neck circumference and shoulder breadth ($r_s = (17) = 0.68$, $p \leq 0.01$).

Table 4.1: Baseline anthropometric variables for all players (Team 1 and Team 2) and for the intervention group (Team 1), separated into forwards and backs

	All Players (30)		**Intervention Group (20)**	
	Forwards	Backs	Forwards	Backs
n	14	16	9	11
Body Mass (kg)	78.1 ± 16.7	66.5 ± 7.5*	79.3 ± 19.5	67.1 ± 6.3
Standing Height (cm)	164.0 ± 5.5	163.6 ± 5.2	163.5 ± 6.1	165.3 ± 4.9
BMI (kg•m^{-2})	28.9 ± 5.3	24.8 ± 2.6*	29.5 ± 5.9	24.6 ± 2.1$^\#$
Neck Circ. (cm)	36.2 ± 2.8	34.4 ± 2.9	36.6 ± 2.5	33.9 ± 1.4$^\#$
Head Circ. (cm)	56.2 ± 0.9	56.0 ± 1.5	55.9 ± 0.8	55.4 ± 1.0
Shoulder Breadth (cm)	38.8 ± 1.8	38.0 ± 2.1	39.6 ± 1.8	38.0 ± 1.2$^\#$
Neck-to-Head Circ. (cm)	0.64 ± 0.05	0.61 ± 0.05	0.65 ± 0.05	0.61 ± 0.03$^\#$

Mean ± SD. BMI, Body Mass Index; Circ, Circumference. * Significant difference ($p \leq 0.05$) between playing positions within all players. $^\#$ Significant difference ($p \leq 0.05$) between playing positions within the intervention group.

4.2 Baseline Neck Strength

4.2.1 Baseline Neck Strength According to Playing Position

In all players, an independent t-test showed that the absolute maximal voluntary contraction (MVC) was greater in the forwards (*n*=13, 137.6 ± 17.3 N) than backs (*n*=17, 123.3 ± 18.4; *t*=2.176, *p*=0.038; Figure 4.1). Within the intervention group, there were no significant positional differences in absolute MVC (*p*=0.219; independent t-test). No positional differences in relative MVC were found overall or within the intervention group (*p*>0.05; independent t-test).

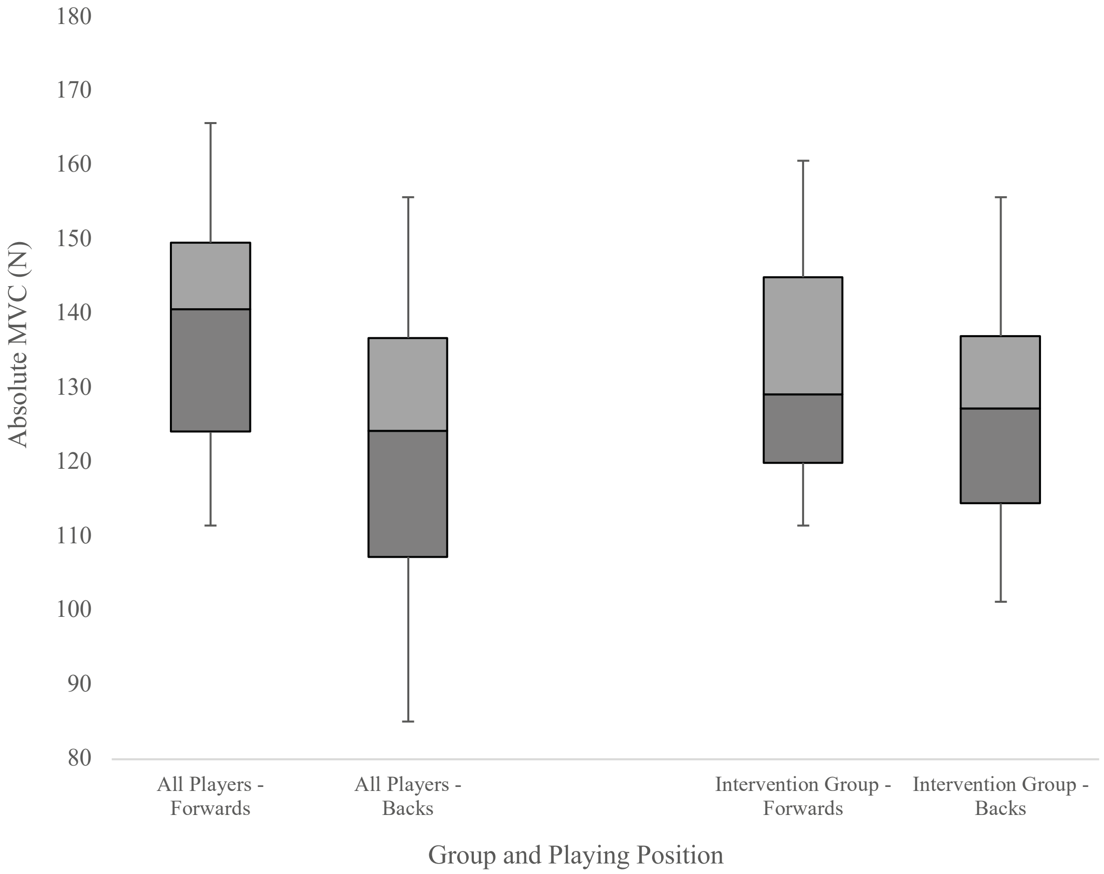


Figure 4.1 Average absolute baseline MVC for all players (Team 1 and Team 2) and the intervention group (Team 1), separated into forwards (Fwds) and backs (Bks)

For all players, Mann-Whitney U tests showed no significant difference between forwards and backs for absolute or relative MVC imbalances between Flx and Ext, or for absolute or relative MVC imbalances between L-Flx and R-Flx, with similar findings for the intervention group separately (*p*>0.05).

4.2.2 Baseline Neck Strength According to Anthropometric Variables

Table 4.2 shows the correlations between five anthropometric variables and both absolute and relative MVC, for all players (n=30) and the intervention group (n=20) separately. Spearman's rho tests showed a weak association between absolute MVC and body mass (R^2=0.151) and relative MVC and body mass (R^2=0.181) for all players, and between relative MVC and body mass (R^2=0.219) for the intervention group separately.

Table 4.2: Correlations between absolute MVC and relative MVC and anthropometric variables at baseline for all players (Team 1 and Team 2) and the intervention group (Team 1)

	All Players		**Intervention Group**	
	p	R^2	*p*	R^2
Absolute MVC (N)				
Body Mass (kg)	*0.041*** ^{NP}	0.151	*0.223* ^{NP}	0.091
Neck Circ. (cm)	*0.167* ^{NP}	0.070	*0.066*	0.195
Head Circ. (cm)	*0.980*	0.000	*0.319*	0.062
Shoulder Breadth (cm)	*0.463* ^{NP}	0.020	*0.282* ^{NP}	0.072
Neck-to-Head Circ. (cm)	*0.306* ^{NP}	0.039	*0.154*	0.123
Relative MVC (N)				
Body Mass (kg)	*0.024*** ^{NP}	0.181	*0.050* $^{\# NP}$	0.219
Neck Circ. (cm)	*0.152* ^{NP}	0.073	*0.454*	0.036
Head Circ. (cm)	*0.216*	0.056	*0.833*	0.003
Shoulder Breadth (cm)	*0.073* ^{NP}	0.114	*0.298* ^{NP}	0.068
Neck-to-Head Circ. (cm)	*0.128* ^{NP}	0.084	*0.395*	0.045

Circ, Circumference. * Significant correlation ($p \leq 0.05$) between MVC and anthropometric variable within all players. $^\#$ Significant correlation ($p \leq 0.05$) between MVC and anthropometric variable within the intervention group. ^{NP} Non-Parametric statistical test.

Spearman's correlations showed no associations between relative MVC imbalances between Flx and Ext, or imbalances between L-Flx and R-Flx and any anthropometric variable (body mass, standing height, head circ., neck circ., neck-to-head circ., or shoulder breadth) for all players or the intervention group separately (p>0.05).

4.2.3 Baseline Neck Strength Imbalances According to Anteroposterior and Mediolateral Directions

As shown in Table 4.3, Wilcoxon signed ranks tests found that irrespective of whether expressed in absolute or relative terms, the MVC in the anteroposterior direction was significantly greater than the mediolateral direction in both all players (n=30) and the intervention group (n=20) specifically. Figure 4.2 shows directional MVC (absolute and relative) for all players and the intervention group separately.

Table 4.3: Baseline absolute and relative MVC for all players (Team 1 and Team 2) and the intervention group alone (Team 1), separated into anteroposterior and mediolateral directions

	All Players		**Intervention Group**	
	Anteroposterior	Mediolateral	Anteroposterior	Mediolateral
Absolute MVC (N)	282.6 ± 68.3	218.7 ± 58.9*	277.3 ± 76.0	213.0 ± 64.6$^{\#}$
Relative MVC (N)	0.38 ± 0.13	0.30 ± 0.11*	0.38 ± 0.14	0.29 ± 0.12$^{\#}$

Mean ± SD. * Significant difference ($p \leq 0.05$) between anteroposterior and mediolateral directions within all players. $^{\#}$ Significant difference ($p \leq 0.05$) between anteroposterior and mediolateral directions within the intervention group.

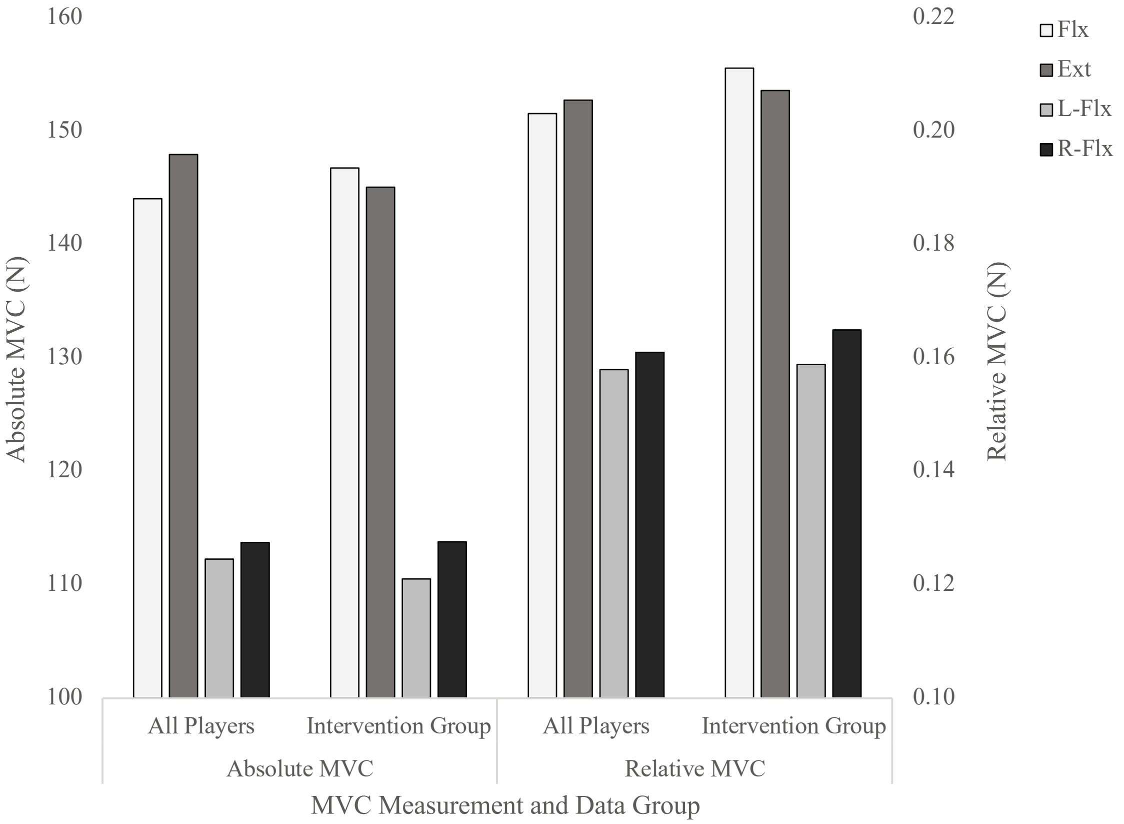


Figure 4.2: Directional comparison of average absolute MVC and average relative MVC at baseline for all players (Team 1 and Team 2) and the intervention group (Team 1)

4.2.4 Baseline Neck Strength According to Rugby Playing Level and Experience

Rugby Playing Level

A MANOVA showed a significant effect of playing level (*F*(2,24)=3.535,*p*=0.045; Wilks'Λ=0.772) and player position (*F*(2,24)=3.433,*p*=0.049; Wilks'Λ=0.778) on all players absolute and relative MVC. There was no statistically significant interaction effect between playing level and player position on all players absolute and relative MVC, (*F*(2,24)=0.250,*p*=0.781; Wilks'Λ=0.980). For the intervention group separately, a MANOVA showed no significant effect of playing level (*F*(2,13)=2.230,*p*=0.147; Wilks'Λ=0.745), player position (*F*(2,13)=1.908,*p*=0.188; Wilks'Λ=0.773) or interaction effect between playing level and player position on absolute and relative MVC (*F*(2,13)=2.957,*p*=0.087; Wilks'Λ=0.687).

The MANOVA analysis showed no significant effect of playing level (*F*(4,22)=0.830, *p*=0.520; Wilks'Λ=0.869), player position (*F*(4,22)=2.099, *p*=0.115; Wilks'Λ=0.724) or interaction effect between playing level and player position on all players absolute and relative MVC imbalances between Flx and Ext and between L-Flx and R-Flx (*F*(4,22)=1.006, *p*=0.426;Wilks'Λ=0.845). For the intervention group separately, a MANOVA showed no significant effect of playing level (*F*(4,11)=0.585, *p*=0.680; Wilks'Λ= 0.825), player position (*F*(4,11)=1.447,*p*=0.283; Wilks'Λ=0.655) or interaction effect between playing level and player position on absolute and relative MVC (*F*(4,11)=0.053, *p*=0.994; Wilks'Λ=0.981).

Playing Experience

Table 4.4 shows the correlations between playing experience (years) and absolute MVC, relative MVC, relative MVC imbalances between Flx and Ext and between L-Flx and R-Flx for all players (n=30) and the intervention group (n=20) separately. A weak association was found between playing experience (years) and relative imbalances between Flx and Ext for all players (Spearman's rho; R^2=0.294) and for the intervention group (Spearman's rho; R^2=0.334).

Table 4.4: Statistical correlations for playing experience (years) with absolute MVC, relative MVC, relative MVC imbalances between flexion (Flx) and extension (Ext), relative MVC imbalances between left lateral flexion (L-Flx) and right lateral flexion (R-Flx) at baseline

	All Players		Intervention Group	
	p	R^2	*p*	R^2
Absolute MVC (N)	0.849	0.001	0.262	0.078
Relative MVC (N)	0.634	0.008	0.337	0.058
Relative imbalances Flx and Ext (N)	0.002*	0.294	0.012#	0.334
Relative imbalances L-Flx and R-Flx (N)	0.903	0.001	0.339	0.057

MVC, Maximal voluntary contraction; Flx, Flexion; Ext, Extension; L-Flx, left lateral flexion; R-Flx, right lateral flexion. * Significant correlation ($p \leq 0.05$) between playing experience and MVC within all players (Team 1 and Team 2). # Significant correlation ($p \leq 0.05$) between playing experience and MVC within the intervention group (Team 1)

4.3 Baseline Neck Strength Endurance Data According to Playing Position, Anthropometric Variables, Anteroposterior and Mediolateral Directions, Rugby Playing Level and Experience

Independent t-tests revealed no significant difference in neck strength endurance (NE; seconds, s) between forwards and backs for all players (n=30; *p*=0.220) or the intervention group separately (n=20; *p*=0.535). NE was not correlated with any anthropometric variable (body mass, head circ., neck circ., neck-to-head circ., shoulder breadth) for all players or the intervention group alone (*p*>0.05).

Wilcoxon signed rank test showed that for all players (n=30), NE in the anteroposterior direction (49.7 ± 32.4 s) was significantly less than the mediolateral (71.5 ± 57.7 s; Z = -2.171, *p*=0.03). A paired samples t-test for the intervention group separately showed that NE in the anteroposterior direction (52.3 ± 16.0 s) was significantly less than the mediolateral (84.4 ± 61.6 s; t(15)2.146, *p*=0.049). There was no significant difference in NE between university-level and higher-level players for all players (*p*=0.725; Mann Whitney) or the intervention group separately (*p*=0.606; independent t-test). Spearman's Rho showed no correlation between NE and playing experience for all players (*p*=0.155, R^2=0.090) or the intervention group (*p*=0.660, R^2=0.017).

4.4 Neck Strengthening Training Programme

4.4.1 Intervention Effect on Average Neck Strength

A paired samples t-test showed a significant difference in the intervention groups average absolute MVC between baseline (128.6 ± 16.2 N) and mid-season (148.8 ± 21.6 N; *t*=5.40, *p*<0.05; Figure 4.3). Independent t-tests showed no significant difference in baseline average absolute MVC between the intervention group (128.3 ± 17.3 N) and Team 2 (131.9 ± 22.9 N, *SE*=7.25; *t* =-0.472 *p*>0.05).

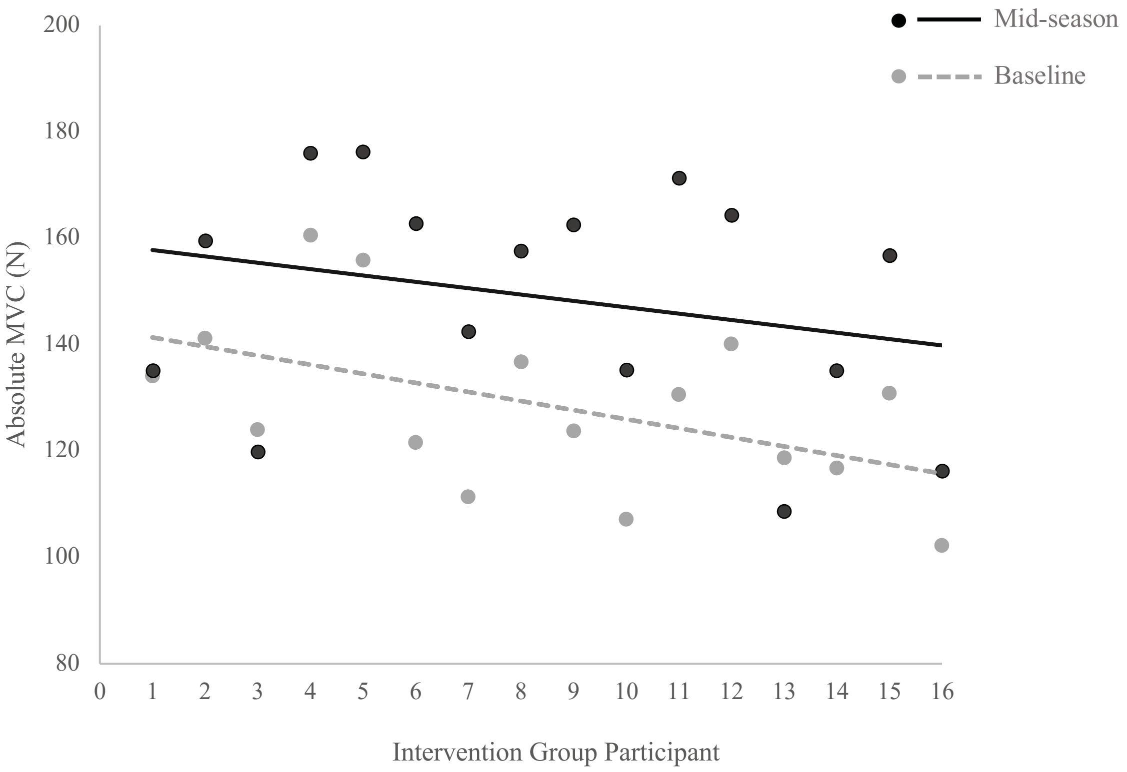


Figure 4.3: Scatterplot representing absolute MVC for the intervention group participants (Team 1), comparison between baseline and mid-season

4.4.2 Intervention Effect on Average and Directional Neck Strength According to Playing Position

No significant differences were found between forwards and backs for the intervention groups mid-season absolute or relative MVC (independent t-tests; *p*>0.05). This was the same for absolute and relative MVC imbalances between Flx and Ext and between L-Flx and R-Flx (Mann-Whitney U; *p*>0.05).

Table 4.5 provides the mean (SD) of directional absolute MVC values at baseline and mid-season for all intervention group participants and for forwards and backs separately. Paired samples t-tests showed a significant difference in directional absolute MVC between baseline and mid-season for Flx, (*t*(15) = -2.847, *p*=0.012), Ext (*t*(15) = -2.204, *p*=0.044), L-Flx, (*t*(15) = -3.252, *p*=0.005) and R-Flx (*t*(15) = -5.013, *p*=≤0.05).

Table 4.5: Absolute MVC in flexion (Flx), extension (Ext), left lateral flexion (L-Flx) and right lateral flexion (R-Flx) at baseline and mid-season for the intervention group with positional comparison

	Flx		**Ext**		**L-Flx**		**R-Flx**	
	Baseline	Mid-season	Baseline	Mid-season	Baseline	Mid-season	Baseline	Mid-season
Total	145.3 ± 24.0	158.4* ± 31.4	142.8 ± 25.6	156.2* ± 32.8	112.1 ± 22.9	138.1* ± 30.5	113.9 ± 20.8	142.6* ± 28.6
Forwards (*n*=7)	149.8 ± 17.1	160.3 ± 32.9	156.2 ± 25.4	172.4 ± 39.8	118.5 ± 21.7	140.6 ± 34.2	117.9 ± 23.5	139.6 ± 25.5
Backs (*n*=9)	141.8 ± 28.8	156.9 ± 32.0	132.3 ± 21.6	143.7 ± 20.6	107.2 ± 23.8	136.1 ± 29.3	110.9 ± 19.2	145.0 ± 32.2

Mean ± SD. Flx, Flexion; Ext, Extension; L-Flx, Left lateral flexion; R-Flx, Right lateral flexion.
* Significant difference (*p*≤0.05) between baseline and mid-season for the total intervention participants (Team 1)

4.4.3 Intervention Effect on Neck Strength Imbalances According to Anteroposterior and Mediolateral Directions

Wilcoxon signed ranks test revealed that mid-season MVC in the anteroposterior direction (272.1 ± 128.6 N) was not significantly greater than in the mediolateral direction (239.9 ± 115.6 N; Z= -1.775, *p*=0.076). Relative MVC in the anteroposterior direction (0.36 ± 0.19 N) was not significantly greater than the mediolateral (0.33 ± 0.19 N; Z= -1.452, *p*=0.147).

4.4.4 Intervention Effect on Neck Strength According to Rugby Playing Level and Experience

Independent t-tests showed no significant difference between higher-level (n=7; 154.0 ± 21.6 N) and university-level (n=9; 144.8 ± 21.9 N) players for mid-season absolute MVC (*p*=0.415), or relative MVC (*p*=0.727). MANOVA analysis showed no statistically significant effect of playing level (*F*(2,11)=0.264,*p*=0.773;Wilks'Λ=0.954), player position ($F(2,11)=1.146, p=0.353$;Wilks'Λ=0.828) or interaction effect between playing level and player position on mid-season absolute and relative MVC ($F(2,11)=0.469, p=0.638$;Wilks'Λ=0.921). A MANOVA showed no significant effect of playing level ($F(4,9)=1.008$, $p=0.452$;Wilks'Λ=0.691), player position ($F(4,9)=0.830$, $p=0.538$; Wilks'Λ=0.730) or interaction effect between playing level and player position on absolute and relative MVC imbalances between Flx and Ext and between L-Flx and R-Flx, ($F(4,9)=0.723, p=0.597$;Wilks'Λ=0.757). Spearman's Rho revealed very weak associations between playing experience (years) and mid-season absolute MVC ($p=0.624$, $R^2 = 0.018$), relative MVC ($p=0.754$, $R^2 = 0.007$), relative MVC imbalances between Flx and Ext ($p=0.180$, $R^2 =0.125$) and between L-Flx and R-Flx ($p=0.944$, $R^2 = 0.000$).

4.4.5 Intervention Effect on Neck Strength According to Neck Strengthening Training Programme Compliance

An independent t-test showed no significant difference in absolute MVC between the intervention groups high-compliance (151.7 ± 17.5 N) and low-compliance (145.9 ± 25.9 N) participants ($t=0.524$, $p=0.608$). There was also no significant difference in the intervention groups MVC improvement from baseline to mid-season between the high-compliance ($n=8$, 25.04 ± 14.52) and low-compliance ($n=8$, 15.50 ± 14.85) groups ($t=0.130, p=0.215$).

4.5 Head Acceleration Event Magnitude

4.5.1 Head Acceleration Event Magnitude According to Mechanisms

Kruskal Wallis tests showed that from all 73 HAE's sustained by the intervention groups iMG wearing players ($n=12$), peak linear acceleration (PLA) and peak rotational acceleration (PRA) were not statistically significant relative to the HAE receiving direction, game event, head action or game event phase in which the HAE was received ($p>0.05$). Further classification details are given in Table 3.6.

4.5.2 Head Acceleration Event Magnitude According to Playing Position, Anthropometric Variables, Rugby Playing Level, Playing Experience and Time in Play

Mann Whitney U tests revealed no significant difference between forwards and backs for PLA (*p*=0.487) or PRA (*p*=0.583). Table 4.6 shows Spearman's rho correlations between anthropometric variables and both PLA and PRA. A weak association was found between standing height and PLA (*p*=0.011, R^2=0.088) and a very weak association between standing height and PRA (*p*=0.698, R^2=0.002). Very weak associations were found between body mass, neck circumference, neck-to-head ratio, head circumference and body mass index with HAE, for both PLA and PRA (*p*>0.05).

Mann Whitney U tests found no significant difference between university-level and higher-level players for PLA (*p*=0.379) or PRA (*p*=0.513). Spearman's Rho revealed a very weak association between playing experience (years) and HAE for PLA (*p*=0.055, R^2=0.051), and no association for PRA (*p*=0.891, R^2=0.000). Spearman's Rho revealed a very weak association between the time in play per game for each participant and the average PLA for each participant per game (*p*=0.390, R^2=0.030) and the average PRA for each participant per game (*p*=0.850, R^2=0.001). Mann Whitney U tests revealed no significant difference between HAE's sustained during the first half and second half of the season for PLA (*p*=0.725) or PRA (*p*=0.229).

Table 4.6: Statistical correlations for head acceleration event PLA and PRA with anthropometric variables

	PLA		PRA	
	p	R^2	*p*	R^2
Body Mass (kg)	0.259	0.018	0.351	0.012
Neck Circ. (cm)	0.444	0.010	0.657	0.003
Neck-to-Head Circ. (cm)	0.292	0.020	0.458	0.010
Head Circ. (cm)	0.427	0.011	0.526	0.007
Standing Height (cm)	0.011*	0.088	0.698	0.002
BMI ($kg \cdot m^{-2}$)	0.808	0.001	0.717	0.002

PLA, Peak Linear Acceleration; PRA, Peak Rotational Acceleration; Circ, Circumference. * Significant correlation (*p*≤0.05) between PLA and an anthropometric variable for the intervention group participants (Team 1)

4.6 Integrated analysis:

Integrated analysis examined whether greater absolute MVC or relative MVC could be a mitigating factor against the PLA or PRA of HAE's.

4.6.1 Head Acceleration Event Magnitude According to Neck Strength

Average Head Acceleration Event Magnitude per Participant

Pearson's correlations found a very weak association between each participant's baseline relative MVC values and each participant's mean PLA (p=0.530, R^2=0.051) and mean PRA (p=0.715, R^2=0.017) for the first half of the season. Mid-season relative MVC was weakly associated with each participant's mean PLA (p=0.828, R^2=0.013) and mean PRA (p=0.925, R^2=0.003) for the second half of the season.

Head Acceleration Event Magnitude of each Recorded Head Acceleration Event

Spearman's rho found weak associations between the baseline absolute MVC of the HAE sustaining participant and the PLA *(*p=0.243, R^2=0.040) and PRA (p=0.415, R^2=0.020) for all HAE's recorded during the first half of the season. The mid-season absolute MVC of the HAE sustaining participants was weakly associated with the PLA (p=0.343, R^2=0.039) and PRA (p=0.511, R^2=0.019) for all HAE's recorded during the second half of the season.

Spearman's rho found a weak association between the baseline relative MVC of the HAE sustaining participant and the PLA (p=0.398, R^2=0.021) and PRA (p=0.767, R^2=0.003) for all HAE's recorded during the first half of the season. The mid-season relative MVC of the HAE sustaining participant was weakly associated with the PLA (p=0.322, R^2=0.043) and PRA (p=0.508, R^2=0.019) for all HAE's recorded during the second half of the season.

Head Acceleration Event Magnitude According to Directional Neck Strength

Using Spearman's Rho, the limited data showed a moderate-strong association between the PRA of HAE's sustained to the left side of the head during the second half of the season and mid-season absolute MVC in L-Flx, R-Flx and L-Flx and R-Flx combined (p=0.041, R^2=0.799). There was also a moderate-strong association between the PLA of HAE's sustained to the back of the head during the first half of the season and baseline relative MVC in Flx (p=0.017, R^2=0.885).

4.6.2 Head Acceleration Event Magnitude According to Neck Strength Endurance

Baseline NE was not associated with the PLA or PRA of all 73 HAE's recorded across the whole game season, or when separated into HAE's sustained during the first half of the season or second half of the season ($p>0.05$). From the small data set, a strong association was found between the PRA of HAE's sustained to the back of the head during the first half of the season and NE in the anteroposterior direction (combined Flx and Ext; $p=0.011$, $R^2=0.978$).

4.6.3 Head Acceleration Event Magnitude According to Neck Strengthening Training Programme Compliance

Mann Whitney U revealed no significant difference between the high and low complying participants for PLA ($p=0.301$) or PRA ($p=0.188$). Independent t-tests showed no significant difference between the high and low compliance groups for each player's average PLA or PRA ($p>0.05$), calculated for HAE's sustained across the whole season, during the first half of the season and during the second half of the season. Spearman's Rho found a very weak association between the neck strength intervention week number and the PLA ($p=0.719$, $R^2=0.002$) and PRA ($p=0.133$, $R^2=0.031$) of all HAE's sustained across the whole season.

Chapter 5: Discussion

The primary aim of this thesis was to quantify neck strength and head-acceleration event (HAE) magnitude in female university rugby union players. The association between neck strength and HAE magnitude was investigated, in addition to the significance of playing position, anthropometric variables, playing experience and HAE mechanisms.

Valid neck strength data was recorded, showing a significant effect of playing position, body mass and neck strength direction. The mean HAE magnitude was lower than in earlier female studies, likely a consequence of the extensive verification process used in this thesis. In terms of the mechanisms of these HAE events, a characteristic whiplash head-to-ground movement was not uncommon, yet no HAE mechanism had a significant effect on HAE magnitude. Further research is also required to identify a potential correlation between neck strength and HAE magnitude.

The overall findings highlight the urgent need for the prioritisation of research into brain-injury biomechanics in women's rugby. An extensive research effort focusing on female-specific injury mechanisms and epidemiology (Meaney, Morrison, & Bass, 2014) is required to safely grow the women's game.

5.1 Anthropometrics and Positional Specificity

In this thesis, whilst at baseline the body mass, along with the absolute maximal voluntary contraction (MVC) of all forward players was significantly greater than backs, other anthropometric variables and relative MVC scores showed no such distinction. Existing male-focused studies (Brand, 2019; Hamilton & Gatherer, 2014; Singa et al., 2020) and previous studies in elite women's rugby (Hene, Bassett, & Andrews, 2011; Nyberg & Penpraze, 2016) have reported considerable anthropometric disparity between different playing positions. These early studies suggest physical adaptation to the physiological requirements of different positional roles, in addition to genetic suitability. The inclusion of anthropometric variables covering a greater range in future research, along with increased positional neck strength training, may generate an association between anthropometric variables and neck strength.

The higher body mass of forward positions recorded in this thesis, is favourable due to forwards greater involvement in tackle-based activities (Dubois et al., 2017). These include rucks, scrummaging, mauls and lifting during lineouts, which require additional strength and power than backs (Dubois et al., 2017). Conversely, back positions demand greater speed and agility, so the lower body mass recorded in this thesis is favourable (Duthie et al., 2003). Nonetheless, it could be postulated that body composition, rather than mass *per se*, may be more indicative of fitness variables (Jones et al., 2016). In particular body fat, which in previous studies of elite females, has been recorded as higher for forwards (30.81 ± 4.56 %) than for backs (26.11 ± 3.81 %; Hene et al., 2011). It is proposed that body fat may operate as a cushion during contact events, by protecting the head from touching the ground during a fall (Duthie et al., 2003; Nyberg & Penpraze, 2016). Future research should therefore seek to ascertain the ideal body composition for different playing positions (Nyberg & Penpraze, 2016).

The average neck circumference in this thesis, irrespective of position, was associated with a greater body mass and a high BMI. Indeed, female-specific clinical data have used neck circumference as a screening measure to identify obesity, with a circumference ≥34 cm considered indicative of a high body mass index (BMI; Barrios, Martin-Biggers, Quick, & Byrd-Bredbenner, 2016; Ben-Noun, Sohar, & Laor, 2001; Tellez et al., 2020). The present thesis found no significant difference in the neck circumference of forwards and backs, with values of 36.2 ± 2.8 cm and 34.4 ± 2.9 cm respectively, converse to Oliver & Du Toit (2008), who found that compared to back positions, the neck circumference of male forwards, particularly from the front row, was significantly greater. The efficacy of neck circumference as a measure of neck strength in female rugby players remains unknown in this thesis. While androcentric studies have reported neck circumference to be a predictor of neck strength in professional male rugby players (Hamilton & Gatherer, 2014), as well as the necks cross sectional area and level length influencing MVC (Hrysomallis, 2016). Moreover, Oliver & Du Toit (2008) found that forwards had stronger necks, yet with less positional difference relative to body weight. Irrespective of sex, and therefore arguably position, a larger neck circumference and neck-to-head circumference ratio are understood to reduce the risk of concussion (Collins et al., 2014).

This thesis suggests that overall, standing height and biacromial shoulder breadth did not significantly vary between positions. For the requirements of second row positional roles, height is advantageous to win the ball in lineouts, enabling a greater overall vertical jump height (Duthie et al., 2003). Whereas, a larger distance between acromia in addition to hypertrophy of shoulder musculature from training, both increase upper body strength and power (Herdem & Kaynak, 2019). A wide shoulder breadth would therefore benefit front row positions during attempts to gain possession of the ball during contact events with the opposition (Duthie et al., 2003). Additionally, the association recorded in this thesis between neck circumference and shoulder breadth may be noteworthy in respect to neck strength. There remains a dearth of literature in women's rugby to draw firm conclusions on the ideal anthropometric measures for different playing positions (Nyberg & Penpraze, 2016); however, regarding untrainable skeletal measurements, such as standing height and biacromial shoulder breadth, effective positional selection is important (Jones et al., 2016).

5.1.1 Implications of Limited Rugby Opportunities for School Girls

In this thesis, there was a lack of positional anthropometric and neck strength differences, indicative of limited positional specialisation. Changing playing positions from one season to the next was commonplace for these participants. For example, a front row player in the current season had played number eight (back row) in the previous season. A back-row player in the current season had previously been a centre. These findings are likely the result of female players typically later entry into rugby and inadequacy of the development pathways in place (Joncheray & Tlili, 2017), due to societal stigmas and a shortage of childhood rugby opportunities for girls (Roberts, Gray, & Camacho Minano, 2019). This is also reported to account of the higher brain injury susceptibility of female players previously recorded (Joncheray & Tlili, 2017).

Limited Playing Experience

The University women's rugby players in this thesis had an average playing experience of 5.5 ± 3.7 yrs., with 47% having commenced rugby over the age of 16 yrs. Similarly, within the French first division squads, 67% of the women had begun rugby after turning 16 yrs., compared to >66% of the men who had started rugby before turning 16 (Joncheray & Tlili, 2017). This thesis provided further evidence that most women's rugby players come from non-contact sports, compared to the majority of men who transfer to rugby from other football codes, including rugby league (Clarke, 2016). Often this is the result of participation barriers for women, which manifest across rugby systems worldwide, including in South Africa, where <50% of provincial unions provide rugby for girls and only 20% of girls participate across all junior age categories (Posthumus, 2013). Women’s late entry into rugby is reported to influence their interpretation of the game and alter their playing style (Dovey, 2016). Additionally, stylistic differences may be due to capability disparities including kicking distance, increasing the running game. It is important to tailor training to the unique requirements of the women’s game, including females’ specific weaknesses and experiences (Clarke, 2016).

In this thesis, the women played for the University first XV team despite their relatively short average playing experience in years. Previous research confirms that not only do women have a delayed start to their rugby careers, women regularly play at higher competitive levels after a shorter time period than men (Joncheray & Tlili, 2017). For instance, in France, women typically start playing rugby competitively at university (34%), whereas the men play competitive rugby earlier at clubs (77%), rather than university (18%; Joncheray & Tlili, 2017). Additionally, twenty years ago the majority of New Zealand’s national team, the Black Ferns, was composed of players who had begun rugby as adults (Chu, Leberman, Howe, & Bachor, 2003). More recently, however, participation opportunities are seen to be improving, as a Global Women’s Survey revealed that 70% of current international women’s players began rugby as teenagers (International Rugby Players, 2021).

Mirrored Training Programmes

This thesis recommends sex-specific and position-orientated training due to female’s physiological differences and shorter long-term exposure to contact sports (Clarke, 2016). Previously, training programmes delivered to females were usually derived from male research, as the vast majority of studies in rugby codes are conducted on men (Clarke, 2016). While well-intentioned, endeavouring to provide an equal opportunities policy for training schedules and activities, only worsens the inequalities between sexes. Future studies warrant sex-segregated research on the demands of the game, advantageous physiological characteristics and the effect of training and recovery, to greater understand female rugby players (Clarke, 2016). The purpose being to reduce the prevalence of injury, specifically neck and head injuries, and to develop position-specific anthropometric variation (Nyberg & Penpraze, 2016).

Findings in this thesis, consistent with Clarke (2016) demonstrate that female players' size, strength, tackle technique, skill proficiency and patterns of play are not comparable to males. However, at equivalent rugby levels, both men and women abide by identical rules (Joncheray & Tlili, 2017), falsely inferring that they are comparable in skill and experience, despite women's rugby having a higher proportion of amateur players relative to men's (Hamlin et al., 2020). These rules, along with injury prevention and return to play protocols, have been developed based on male-derived data (Cross et al., 2019; Hendricks, Karpul, & Lambert, 2014; Stokes et al., 2019; Tucker et al., 2017) and may therefore have limited efficacy in females. Interventions must also consider playing history in order to effectively reduce the risk of injury. A strong case exists for the development of a female-specific evidence base, upon which to derive injury prevention protocols for women's rugby.

5.2 Quantifying Head Acceleration Events in Female Rugby Athletes

5.2.1 Head Acceleration Data Collection Methodologies

Bespoke, well-coupled instrumented mouthguards (iMG) were used to record head acceleration events in this thesis (Greybe et al., 2020; Liu et al., 2020). Instrumented skin patches have previously been used in collision sports (King et al., 2019). However, dermal artefact due to defective coupling between the mastoid process and skin can causes data inaccuracies, overestimating peak linear acceleration (PLA) and peak rotational acceleration (PRA; Wu et al., 2016). The improved coupling in this thesis limited artefact and improved the reliability of the HAE data, resulting in HAE data of a lower magnitude than recorded previously (King et al., 2019). Additional post-processing steps were taken in this thesis, all HAE's were both video-verified and waveform-verified and a 4th order Butterworth filter was applied to all data. This meant fewer HAE's were recorded per game than previously reported (Kieffer et al., 2020; King et al., 2019). While potentially eliminating some true positives, these post-processing steps ensured that no artefacts, such as bites and shouts were included in the final data set. There is an obvious absence pertaining to comparative females iMG studies (Kieffer et al., 2020). Instead, existing research has largely used externally mounted sensors, such as instrumented headgear, giving high, erroneous values (Patton et al., 2020). Greater cross-comparison between studies would benefit from a minimum set of recording, processing and reporting standards for head impact telemetry data to be considered reliable.

This thesis successfully quantified head-acceleration events in female university rugby union players. The median PLA and PRA for all HAE's in this thesis was 11.9 ± 7.3 *g* and 830.9 ± 646.9 rad•s^{-2} respectively. Only a small number of publications have used mouthguard head impact telemetry in women's rugby; however, the PLA and PRA values reported in this thesis are lower than in previous studies (King et al., 2015). Of interest, a recent iMG study of female collegiate rugby players, reported a median PLA of 15.2 *g* for direct head impacts and 13.9 *g* for body impacts (Kieffer et al., 2020). Such inconsistencies could be due to the rigour of the verification process, filtering procedures and more extensive exclusion criteria in this thesis than reported in previous studies. Indeed, Kieffer et al., (2020) reported a waveform verification process, eliminating those with considerable noise, yet these authors have, however, included impacts of short duration (<7.5 ms). According to the criteria used in this thesis, these may be considered spurious impacts such as bites, further limiting in-depth interstudy comparisons here.

5.2.2 Head Acceleration Event Magnitude

In this thesis, rugby playing experience, playing position, anthropometric variables and time in play only had a minor influence on the variability of HAE magnitude. When independently assessed, no HAE mechanism (direction of head movement, game event, head action or game event phase) had a significant effect on PLA or PRA. Previous studies have focus more on the relationship between HAE mechanism and the prevalence of recorded head injuries or concussions, rather than their magnitude (Cusimano et al., 2013; Roberts et al., 2017). As many independent and extraneous variables contribute to HAE magnitude, future research will require substantially greater participant numbers to adequately power the studies.

Direction of Head Movement

The most frequently recorded head movement was backward extension (49%), followed by left lateral flexion (21%), right lateral flexion (16%) and forward flexion (14%). Data from men's high school and collegiate American football show a corresponding distribution of head movement directions, with backward extension being the most prevalent (Broglio et al., 2010; Mihalik et al., 2007; Urban et al., 2013). Inter-sport findings are not directly applicable, due to different rules and protective equipment (King et al., 2015), along with differing recording, verification and filtering methods. Within men's rugby, King et al. (2015) reported a more even distribution: backward extension (29%), left lateral flexion (23%), right lateral flexion (21%), forward flexion (24%) and other (3%). Dissimilar to the findings in this thesis, previous male-focused studies have found that regardless of sport, front-on tackles result in higher impact magnitudes (Tucker et al., 2017).

Game Event

In this thesis, the prevalence of different HAE game event types were: during the tackle as the tackler (52%), during the tackle as the ball carrier (32%), rucks (15%), mauls (1%), with no verified HAE's in lineouts or scrums. Previous studies have also reported a higher incident rate for the tackler (Tierney et al., 2016). Such as in elite men's rugby, where video analysis identified that 70% of concussive tackles were sustained by the tackler and 30% by the ball carrier (Cross et al., 2019). This thesis found that the game event did not significantly affect HAE magnitude; however, Cross et al., (2019) recorded a 37 times greater concussive risk from high tackles than passive shoulder tackles. Such discrepancies may be influenced by methodological inconsistencies, with Cross et al., (2019) investigating clincally diagnosed concussions, opposed to the magnitude of head accelerations investigated in this thesis. The extent to which concussion risk is increased by additional tackle-related factors, including collision tackles (Fuller et al., 2010; Suzuki et al., 2019), tackle speed (Quarrie & Hopkins, 2008) and high tackles, requires further investigation, as Cross et al., (2019) included no female data in these results.

Head Action

From the observed and verified HAE's, direct head impacts on hard body parts were recorded most frequently (46%). Despite head action having no significant effect on head acceleration magnitude in this thesis, in men's rugby, initial contact with the tackler's head or neck is reported to significantly increase concussion likelihood (Cross et al., 2019; Suzuki et al., 2019; Tucker et al., 2017). In this thesis, also common were head to ground impacts (26%), which in men's rugby are reported to have a high risk of concussion (Cross et al., 2019). There was also a high frequency of indirect impacts to the head (19%), explained by rugby's composition, where during fights for possession of the ball in mauls, rucks and scrums, accelerations are regularly transmitted through the body to the neck (Cross et al., 2019).

Direct head impact on a soft body part, which included the torso (4%) and other head actions (4%) accounted for minimal HAE's. The findings in this thesis greatly differ to a study of elite men, where the torso was the most frequent head impact location (Cross et al., 2019). Instead, substantially more HAE's recorded in this thesis involved a characteristic whiplash head-to-ground movement. This has not been reported previously as a predominant HAE mechanism in the existing androcentric rugby studies (Tierney, Lawler, Denvir, McQuilkin, & Simms, 2016). Existing research in men's rugby has instigated greater emphasis to be placed on executing tackles where the ball-carrier's shoulder is the first point of contact, opposed to the head or neck (Suzuki et al., 2019). Based on the observed differences in the head action of female players in this thesis, relevant coaching strategies are required in women's rugby, specifically designed to minimise the types of injuries females are sustaining.

Game Event Phase

The vast majority of HAE's were sustained during the fall, when the players feet were not in full contact with the ground (56%; PLA: 11.9 ± 4.7 *g*, PRA: 830.9 ± 646.9 rad•s^{-2}). This was followed by HAE's sustained when the player was standing, supporting their own body weight (32%; PLA: 12.0 ± 10.0 *g*, PRA: 874.9 ± 809.7 rad•s^{-2}). Similarly, analysis of 464 head injury events in men's rugby involving the tackler or ball carrier, found that standing upright resulted in a higher impact magnitude and was 1.5 times more likely to require a HIA than a tackle where the player was bent at the waist (Tucker et al., 2017). The remaining HAE's were received whilst the player was on the ground (12%; PLA: 10.2 ± 8.2 *g*, PRA: 791.8 ± 200.7 rad•s^{-2}). An emphasis on safe fall training in women's rugby is therefore required, given the large number of HAE's sustained during the fall and on the ground in this thesis.

Head Acceleration Event Positional and Anthropometric Comparisons

Player position had no significant effect on HAE magnitude. To discern the effect of player position on HAE mechanisms would require a larger dataset than that available in this thesis. For the 30 HAE's sustained by backs, the median PLA was 13.3 ± 6.7 *g* and PRA 852.1 ± 441.4 rad•s^{-2}. The 43 HAE's received by forwards had a comparable median PLA of 11.7 ± 8.5 *g* and a lower PRA of 808.8 ± 801.7 rad•s^{-2}. This corresponds with iMG data collected on male rugby players, where a lower mean PRA was recorded for forwards than backs (King et al., 2015). Participant body mass, neck circumference, neck-to-head ratio, head circumference and BMI did not correlate with PLA nor PRA, although standing height correlated with PLA only. The reason for this may be related to the high frequency of head to ground HAE's observed in this university cohort. Large scale studies, conducted on females with a greater anthropometric range, are required to investigate this further.

Head Acceleration Event Magnitude and Time in Play

No trends were observed between the time in the game that HAE's occurred and the corresponding magnitudes, or the magnitude of HAE's recorded in the first and second halves of the season. Previous studies of male amateur rugby players have referenced the negative performance effect of fatigue (Davidow et al., 2020), and attributed a greater number of injuries during the second half of games to this (Burger et al., 2017). This was not evident in the present thesis; however, given the technological and logistical limitations in this thesis, no conclusions can be drawn as to the probable reason for this.

5.3 Developing Effective Neck Strengthening Training Strategies

5.3.1 Neck Strength Data Collection Methodologies

The custom-built isometric neck strength testing apparatus (INSTA) used in this thesis effectively quantified directional neck strength and was an advancement on manual assessments (Harris et al., 2005), hand-held dynamometers (Ashall, Dobbin, & Thorpe, 2021), headbands attached to tension scales (Collins et al., 2014) and Gatherer systems (Hamilton & Gatherer, 2014). These early methods are associated with low reliability, inter-tester variability and safety concerns (Collins et al., 2014; Nazarahari, Arthur, & Rouhani, 2020). Furthermore, the scrum position simulated in this thesis was more representative of a rugby stance than the previously favoured seated testing position (Dvir

& Prushansky, 2008; Oliver & Du Toit, 2008). As in collision sports, loading of the spine predominantly occurs in a neutral, horizontal position (Salmon et al., 2015). Indeed, the effective device developed by Mcbride & Oxford (2020), also utilised a standardised quadruped position and reported excellent intra-rater reliability. Additional measures were taken to further improve the repeatability and reliability of measurements in this thesis. As implemented in prior neck strength protocols, to increase the degree of reliability during repeated testing sessions (Dezman et al., 2013; Salmon et al., 2015), the participant was restrained around the torso and at thigh level. These measures were taken to isolate the cervical musculature and intentionally compromise the functionality of accessory movement (Salmon et al., 2015). A supporting chest plate provided trunk stabilisation, previously considered fundamental for valid and reliable measurements of neck strength (Oliver & Du Toit, 2008).

During data collection, the present thesis employed verbal encouragement and a competitive strategy; informing participants that their neck strength was slightly lower than others in the same playing position. Individual differences and personality traits, such as conscientiousness, are suggested to influence the effectiveness of motivational strategies (Voor, Lloyd, & Cole, 2013). It is therefore certainly plausible that a small performance reduction may have occurred if the participant interpreted the motivation or other team members presents as a stress factor (Voor et al., 2013). To give all participants an equal opportunity of reaping the benefits, the level of encouragement remained consistent between individuals, with the same researchers, phrases and keywords used.

5.3.2 Investigating the Benefits of a Neck Strengthening Training Programmes

Given the association between neck strength and head motion (Wood et al., 2019), the prescribed intervention targeted neck musculature in order to improve neck strength and stability. Evidence is limited supporting the direct relationship between neck strength and concussion; however, neck strengthening remains a prominent modifiable risk factor, targeted to reduce the magnitude and severity of head impacts in rugby (Chavarro-Nieto, Beaven, Gill, & Hebert-Losier, 2021). Additionally, on the recommendation of prior research, the intervention was sport and gender specific and appropriate for the team and session type (Wilcox et al., 2014). Dissimilarities in participant sex, age and playing experience can explain why results differ from previous studies, which predominantly focused on elite, male athletes (Hamlin et al., 2020).

Neck strength training was undertaken twice per week, as this is proven to cause the greatest MVC increase, specifically in extension, opposed to once per week (Pollock et al., 1993). While an improvement in MVC was recorded between baseline and mid-season for the intervention group as a whole, greater improvements were recorded in the high-compliance group. Although, there was no significant difference between the high-compliance and low-compliance groups mid-season MVC scores. The COVID-19 pandemic prevented the planned continuation of the intervention and post-season comparison. The participants were supervised during all sessions, as the presence of a strength and conditioning coach is strongly advised for resistance training to have the most beneficial effect on performance (Coutts, Murphy, & Dascombe, 2004). Nonetheless further research is required on the dose-response relationship for resistance training in females (Lesinski, Prieske, & Granacher, 2016).

Neck Strength

Following the neck strengthening training, the intervention group recorded a significant difference between baseline and mid-season measures of absolute MVC, in the directions of flexion, extension, left lateral flexion and right lateral flexion. These improvements demonstrate the trainability of neck strength in female players and are promising. It is anticipated that absolute MVC would have recorded a greater significant difference between baseline and post-season, had COVID-19 not prevented post-season data collection. Previously, isometric exercises have also resulted in MVC improvements in all directions for professional male players (Chavarro-Nieto et al., 2021). Although, notably for both males and females, extension is reported to provide more consistent measures of MVC across time, whereas flexion has demonstrated a greater learning effect (Salmon et al., 2015). Despite the familiarisation period, the effect of learning may therefore have been a factor when measuring flexion in this thesis.

The intervention had a positive effect on reducing the neck strength imbalances between anteroposterior and mediolateral directions. Prior to the intervention, baseline MVC (absolute and relative) had been significantly greater in the anteroposterior direction.

Literature is scarce comparing neck strength between anteroposterior and mediolateral directions; however, further classification of forwards may have highlighted positional imbalances. In particular, stronger mediolateral MVC has been recorded for male second-row forwards, as a result of the large amounts of lateral movement they experience whilst scrummaging (Oliver & Du Toit, 2008). Whereas front-row forwards, who are bound to the opposing teams' front row, experience less transverse horizontal force and largely move within the vertical plane. Therefore, whilst scrummaging, male front-row forwards have recorded significantly greater anteroposterior MVC than mediolateral MVC (Oliver & Du Toit, 2008).

Baseline MVC data from all participants in this thesis, showed that forwards were significantly stronger than backs, a finding that is consistent with earlier literature (Hrysomallis, 2016; Oliver & Du Toit, 2008). In this thesis, the participants also recorded a significant association between the baseline MVC (absolute and relative) and body mass of all players as well as a significant positional difference in body mass, which may explain why relative MVC was not significant between positions at baseline. Previous studies of males and females also report lower positional variability and limited positional differences in relative MVC, despite recording significantly greater absolute MVC for forwards (Mcbride & Oxford, 2020; Oliver & Du Toit, 2008). Taken together, these studies demonstrate that body mass was highly influential on MVC, and that the difference in MVC between forwards and backs was negligible, a direct reflection of the participants minimal position-specific training. In this thesis, the intervention did not result in any significant difference in positional MVC imbalances (absolute and relative) between flexion and extension, or between left and right lateral flexion. The minimal effect of playing position on baseline and mid-season MVC in this thesis highlights the need for position-specific neck strength training.

All participants were stronger in extension than flexion at baseline. The forwards, however, were 7.00 N stronger in extension than flexion, whilst the backs were only 1.58 N stronger in extension than flexion. The more proportional neck strength of backs across flexion and extension has been recognised in earlier male and female rugby studies (Chavarro-Nieto et al., 2021; Oliver & Du Toit, 2008; Suryanarayana & Kumar, 2005). Whereas, the extensor muscles of forwards are often considerably stronger in extension than flexion, with a greater cross-sectional area and postural role (Oliver & Du Toit, 2008; Salmon et al., 2015; Suryanarayana & Kumar, 2005). This reflects forwards greater involvement in scrums, where neck strength in extension is valuable in order to maintain scrum stability and when executing a head up position whilst binding (Oliver & Du Toit, 2008). In the general population, the difference between neck flexion and extension strength is reported to be ~60% (Oliver & Du Toit, 2008). In line with previous literature, there was minimal disparity between neck strength in left and right lateral flexion, due to the bilateral alignment of cervical musculature (Oliver & Du Toit, 2008). Whilst more balanced neck strength is advantageous in soccer at reducing head acceleration (Dezman et al., 2013), the benefits remain to be investigated in rugby.

Neck Strength Endurance

Muscular endurance may also be an important consideration in respect to rugby performance and injury prevention (Hrysomallis, 2016). However, endurance studies of the neck muscles are uncommon and interstudy comparison is challenged by differences in methodologies (Liss, Sanni, & McCully, 2020). The present thesis found no significant difference in baseline neck strength endurance between playing positions or playing levels. There were no correlations between baseline neck strength endurance and any anthropometric variable or playing experience. This thesis could not confirm a weak correlation between neck strength and neck strength endurance as previously reported (Hamilton et al., 2014). More research is required to further study neck strength endurance in the rugby context, such as scrum-specific fatigue (Hamilton et al., 2014).

5.4 Neck Strength as a Head Acceleration Event Reduction Method

5.4.1 Investigating the Benefits of Neck Strengthening Training Programmes on Head Impact Telemetry Data

In the present thesis, compliance with, or progression of the neck strengthening intervention had no effect on the measured PLA or PRA in competitive matches. The efficacy of neck strengthening in reducing HAE magnitude remained relatively unknown following previous studies, which employed resistance training to improve head control with varied results (Wood et al., 2019). The majority of prior neck strengthening interventions were conducted on males, with one such intervention in professional men's rugby being deemed ineffective (Naish et al., 2013). Female neck strength is reportedly weaker than males (Mansell et al., 2005), with Williams et al., (2021) reporting the isometric neck strength of female university rugby players to be 47% lower than their male counterparts. This strength difference is likely a significant contributor to the greater peak head acceleration values and head injury metrics recorded in females, following simulated sub-concussive chest impacts by Nazarahari et al., (2020). Concussion likelihood (Head Injury Criterion; HIC) for females was also reported as being 5.9% higher than males for impacts of the same magnitude (Bigham & Hanlon, 2020). McGroarty et al., (2020), suggest that weaker neck strength is a prominent reason why females are more susceptible to concussion and advocate for further research in this area. These findings question the applicability and efficacy of results from androcentric studies being generalised to female athletes.

The absence of a correlation between the progression of the neck strength intervention and the recorded HAE magnitudes could be affected by several factors. These include the mouthguard recording techniques and total number of recorded HAE's, in addition to neck strength changes. It is also feasible that the interventions duration and frequency were insufficient, as early studies report muscular hypertrophy of human limb muscle to occurs following eight to 16 weeks of resistance training (Conley, Stone, Nimmons, & Dudley, 1997). However, a more recent intervention recorded neck girth and strength improvements for 15 male and two female adolescent participants, following a comparable eight-week intervention (Eckner et al., 2018). Future studies require a larger data set and longer duration to investigate this relationship.

Neck Strength, Neck Strength Endurance and Head Acceleration Event Magnitude

In this thesis, the association between neck strength and HAE magnitude was inconclusive, as no correlation was found between MVC (absolute or relative) and PLA or PRA, for baseline or mid-season data. Previous studies have reported that improving neck strength reduced the total rotational acceleration of the head and traumatic brain injury (TBI) severity (Daneshvar et al., 2011). One method used to investigate this association was a neck and head testing fixture, used to simulate different neck strengths (Bigham & Hanlon, 2020). Methodical differences may therefore explain differences in findings. The limited data in this thesis suggests an association between HAE magnitude, categorised by HAE direction, with directional MVC. However, given the low participant numbers in this thesis, analysis relating to the breakdown of directional neck strength is underpowered. A greater PRA would be expected during HAE's to the front of the head resulting in extension, as greater torque has been recorded in the neck extensor muscles, whilst the flexor muscles exhibited the least torque (Seng, Peter, & Lam, 2002).

The present thesis recorded no significance between neck strength endurance and HAE magnitude. It has been postulated that low neck strength endurance is correlated with concussion susceptibility caused by head impacts (Liss et al., 2020). Yet the study conducted by Liss et al. (2020) was not rugby specific and despite having an even number of males and females, was only based on twelve healthy participants. Further sports-specific research is required to identify any association between neck strength endurance and injury probability in rugby, in addition to identifying any significant association between HAE magnitude and directional neck strength endurance.

Rugby Playing Level, Playing Experience, Neck Strength and Head Acceleration Event Magnitude

At baseline, the intervention and HAE telemetry study participants recorded no significant difference between university-level and higher-level players for absolute and relative MVC. Significant differences in injury prevalence data have previously been recorded between community-level and elite male players (Roberts et al., 2013; Williams et al., 2013). Given this, it is possible that for the female players in this thesis, the performance gap between university-level and higher-level players was insufficient, as for both groups, the average playing experience (years) was relatively low. For females, comparison between playing levels with greater disparity, such as community-level and elite may highlight differences in their MVC. Due to different positional requirements regarding neck strength, player position was incorporated into the analysis, but yielded no significant interaction effect on MVC (absolute or relative). At mid-season, there remained no significant difference between university-level and higher-level players MVC (absolute or relative), including with player position incorporated. However, the difference in neck strength between the two playing levels had reduced at mid-season.

Playing experience in years did not correlate with MVC (absolute or relative) at baseline or mid-season. It must be considered that the participants with the greatest years' experience were not necessarily the elite level players. Therefore, MVC was predicted to be unaffected by playing experience as neck strengthening training was a new consideration for all participants, and due to the low mean years of experience within the team. However, the physical requirements of different playing positions is an important factor to consider, as the analysis combined all players. Relative MVC imbalances between flexion and extension were not correlated with playing experience at baseline but were correlated at mid-season following the intervention. Imbalances between left and right lateral flexion did not correlate with playing experience at baseline or mid-season. Previous neck injuries and playing position may have affected these results, in addition to the small sample size; however, these findings may demonstrate a positive intervention effect at reducing neck strength imbalances.

In accordance with the minimal influence of playing experience on MVC, no significant relationships were recorded in this thesis between rugby playing experience, in years or by level, and HAE magnitude. There was a weak association, however, between playing-experience and PLA (p=0.055, R^2=0.051). Review papers have noted that during contact events in rugby, certain tackle techniques reduce the risk of injury, although no distinction was made between males and females (Hollander, Ponce, Lambert, Jones, & Hendricks, 2021). Effective tackle and falling technique would be expected to reduce head acceleration during the fall, potentially more so than neck strength. This is of interest given that the fall was the phase of the game event during which the majority of HAE's in this thesis were sustained.

In this thesis, an insufficient number of higher-level participants and verified HAE's prevented meaningful conclusions to be made on the association between playing experience, falling technique and HAE magnitude. However, a safe falling technique to reduce injury severity would likely rely on appropriate and effective coaching throughout the players rugby careers, irrespective of playing experience. The RFU's existing injury prevention program, 'Activate', includes strength and movement control exercises for the neck and head, but was developed from androcentric research (Attwood, Roberts, Trewartha, England, & Stokes, 2018; Hislop et al., 2017). Existing programmes such as this should not be presumed applicable to females. New interventions must be developed, or modifications made to existing programmes, based on female-focused studies.

5.5 Future Directions

Measuring neck strength and implementing relatively simple neck strength interventions has the potential to significantly reduce mild traumatic brain injury (mTBI) prevalence in rugby on a global scale. Future studies could include training as well as competitive game data, as different playing intensities influence injury data, including HAE prevalence and magnitude (King et al., 2019). Alongside research on female HAE mechanisms, the application of inertial neck trauma studies can extend to the majority of contact and collision sports (Salmon et al., 2015). This research is also valuable in non-sporting fields, such as to improve the health and safety of the wider population during motor vehicle crashes (Bose, Segui-Gomez, & Crandall, 2011). In the process of conducting this pilot research in women's rugby, additional aspects game where females are disadvantaged became apparent. These incidental findings are also applicable to women's sport and female sport science in general. Future studies in these areas may improve the performance capabilities of females, in areas where under-research perhaps limited their potential (Emmonds et al., 2019).

5.5.1 Female Performance and Recovery Indicators Database

This thesis uncovered a noticeable absence of representative measures of female anthropometrics at present, with some models being based on a single female participant (Roos, Vasavada, Zheng, & Zhou, 2020). There is also a dearth of papers that have monitored female recovery patterns and long-term implications of concussion (Spani, Braun, & Van Eldik, 2018). Thus, there is an urgent requirement for an objective platform of normative female anthropometric and physiological measures (Nyberg & Penpraze, 2016). Furthermore, an extensive, average directional neck strength database would enable comparisons to be made with females from the same age bracket. Such information would be beneficial to coaches and medical practitioners to identify neck strength abnormalities and monitor progress during training and rehabilitation (Posthumus et al., 2020; Salmon et al., 2015). This would also be useful during talent identification and aid the detection of athletes at a higher injury risk due to low and/or imbalanced neck strength (Dezman et al., 2013). To maximise the value of these datasets, further research on females is required, to understand the physiological and contextual factors that influence the success of their intervention (Emmonds et al., 2019).

5.5.2 Targeted Education and Training Strategies

This thesis and prior research support the inclusion of neck strength training within women's rugby strength and conditioning programmes (Emmonds et al., 2019). Such programmes must be suitable for the participants physiological needs, including sex (Argus, Gill, Keogh, Hopkins, & Beaven, 2010) and would benefit from being position-orientated (Posthumus et al., 2020). It is proposed that feedback from a neck strength testing device may encourage greater compliance to neck strengthening training (Salmon, Hancock, Sullivan, Rehrer, & Niven, 2018). In order to implement such programmes in women's rugby, further sex-specific research is required, including on the most effective training stimuli to optimise performance and improve safety (Nyberg & Penpraze, 2016). The results from this thesis, particularly the high incidence of head to ground contact, indicate that specific tackle and fall technique training can benefit female players. The female players in this thesis had an average of five years playing experience. This is consistent with the playing experience of female university players reported by Williams et al., (2021). These authors reported that the corresponding male team had an average of 13 years' experience, despite no differences in the average age of both teams. Williams et al. reported uncontrolled whiplash in over 50% of recorded female head impacts but only 0.5% of male impacts. Collectively, these findings suggest that fall and tackle training afforded to the male players during their developmental years has not been available for most female players. Future research findings may warrant change on a wider level to how tackle and fall techniques are taught to women's rugby teams.

5.5.3 The Provision and Standard of Women's Rugby Equipment and Facilities

The results from this thesis suggest that it is a priority for women's rugby to address safety concerns associated with HAE. Once this has been addressed, research attention can turn to developing wider aspects of the game for females using female focused studies. Compared to males, for example, females have smaller average hand dimensions (Tilley, 2002), are approximately 7% smaller (Roser, Appel, & Ritchie, 2013) and have lower kicking speeds (Sakamoto, Sasaki, Hong, Matsukura, & Asai, 2014). Nevertheless, in rugby, the ball size, crossbar height and pitch dimensions are identical for males and females. The extent to which equipment equalities limit female's performance should be investigated, and justified changes made.

As the popularity of women's rugby continues to grow, the provisions of facilities in women's rugby should improve, as currently they are often of a noticeably lower standard than the comparable men's team. Illustrated by the 2020 six nations Wales-Scotland games where the women's team played on artificial turf, whilst the men played on well-manicured grass (Jones, 2019). Artificial turf is reported to increase overuse injuries (Lanzetti et al., 2017), occurring at 4,740 injuries per 1,000 days, compared to 2,481 per 1,000 days on grass (Bashir, 2020). Improving facilities in women's rugby should therefore contribute to a decrease in women's injury prevalence. Beyond the playing field, inequalities were recently apparent in the advertisement of the Canterbury 2020 Irish jersey, marketed by unknown models for the women, yet professional rugby players for the men (Sky sports, 2020).Hence, to resolve preconceptions and inequalities in women's rugby and enable the games continued development, first and foremost a change in the language and practices that those in the position of power, including the media and rugby law creators use is required. As this influences the discourses that inform the public's understanding and perception of women in sport (Sam, 2019).

5.5.4 Research on the Influence of Sex and Gender

Females remain a clinical population in wider science, frequently portrayed as anomalies to the standard 'default male' (Woitowich & Woodruff, 2019). Research on vehicle safety measures primarily use male proportions for crash test dummies (Ott et al., 2020), compromising females' safety and potentially contributing to females 47% higher injury likelihood during collisions (Bose et al., 2011). Female inclusion in all medical studies is critically important.

As with the present thesis, it is not only important to separate men and women's rugby teams, it is also fundamental to distinguishes between sex; biological and defined by genetics, physiology and hormones, and gender; socially constructed and attributed to appearance, thoughts and behaviours (Keet, Roy, & Henry, 2019; Woitowich & Woodruff, 2019). This is because, sport dependent, the performance gap between males and females is 10-50% (Hilton & Lundberg, 2020). Given the large involvement of upper body muscle mass and strength in rugby, the difference is more prominent at 10-160% (World Rugby, 2020). Regarding head and neck forces, these are cited as 20-30% greater in elite male rugby players than females (World Rugby, 2020). Allowing both sexes to participate alongside each other in rugby can increase injury risk by a minimum of 20-30% due to the differences in mass, speed, strength and resultant kinetic and kinematic forces (Ingle, 2020). However, segregation of sports according to sex creates complications for transgender athletes (Hilton & Lundberg, 2020). Central to the International Olympic Committees policy on transgender athletes are the perhaps conflicting objectives of inclusion and fair competition (Hilton & Lundberg, 2020). Safety concerns are prevalent, illustrated by World Rugby's recent decision to exclude transgender women from international women's competition (Ingle, 2020). Nonetheless, there are no direct studies on transgender women's rugby players, meaning that many questions remain unanswered and further research is required (Cirillo et al., 2020).

Adverse and enhancing physiological responses depending on the stage of the menstrual cycle pose a challenge to research methodologies (Sims & Heather, 2018), with negative performance effects testified by 77% of elite athletes (Findlay, Macrae, Whyte, Easton, & Forrest, 2020). Research on the effect of female hormones on the body's response to resistance training generate conflicting findings (Thompson, Almarjawi, Sculley, & Janse de Jonge, 2020) and their effect on neck strength training specifically requires investigation. In respect to TBI, sex and hormones are recorded to influence the series of responses following a head injury (Roof, Duvdevani, & Stein, 1993). Although favourable effects of progesterone are mainly restricted to animal models (Theis & Theiss, 2019). Further research on the effect of hormones, specifically oestrogen, progesterone and testosterone is paramount to understand the potential implications of sex on rugby performance and response to TBI.

5.6 Limitations

Data collection was compromised by external factors which limited the extent of statistical analysis that could be conducted, decreasing the potential strength of the thesis's findings. The COVID-19 pandemic caused a premature end to the neck strengthening training programme for the intervention group and also terminated the game season. Therefore, end of season anthropometric, neck strength and neck strength endurance measurements were not obtained for all players (Team 1: *n*=20; Team 2: *n*=10). This prevented comparisons from being made between the intervention group and Team 2 at post-season. Data was also unable to be collected from additional women's university teams for greater comparison as intended. The shortened data collection window and participant numbers limited the correlations which could be made between neck strength and head acceleration. A longer intervention, or total duration may be required to record significant results. Additionally, the intervention would benefit from a control group composed of participants from the same team. Systematic and manufacturing limitations were encountered with the iMG system. HAE's were discounted in instances where maxima data with no waveform was recorded, as they could not be verified. This greatly reduced the data set size from the number of HAE's observed using video analysis, yet it also improved the quality of the data set. Lastly, the nature of the thesis and its season-long duration were likely to influence the degree of participant compliance and dropout rate. The combination of these limitations resulted in the small data set.

A prominent, longstanding issue in head impact telemetry studies is the absence of standardisation when recording and reporting HAE data, including within verification processes. With the growing research focus on investigating the association between neck strength and HAE data, consistency issues are now arising when quantifying neck strength. This includes the possible need to adjust for body weight, standing height and the participants physical condition (Nazarahari et al., 2020). Future studies require standardisation, through the refinement of testing apparatus and protocols.

5.7 Conclusions

Precursors of neck strength, and the influence of neck strength on HAE telemetry data were investigated in this thesis. Mid-season isometric neck strength was significantly greater than baseline following a progressive neck strengthening intervention program. These preliminary findings support the efficacy of this intervention and the benefits of neck strength training. The effectiveness of this intervention at reducing HAE magnitude was inconclusive and warrants further investigation, with a larger study population and longer intervention duration.

This thesis was strengthened by the purpose-built INSTA, and data collection procedure, which enabled reliable measures of MVC across four directions, and the head impact telemetry system, which effectively quantified the PLA and PRA of head acceleration events. The commercially available, custom-built INSTA and testing protocol can be easily replicated in future research studies. The relatively lower HAE magnitudes recorded in this thesis compared to earlier literature are directly reflective of the mouthguard's direct sensor-skull coupling and this thesis's methodology, including the rigour of verification process. The methods used to record, process, and report HAE data require standardisation in future studies, to validate their significance. Of importance, the intervention was specifically designed for females. Analysis benefitted from the inclusion of relative neck strength in addition to absolute neck strength. Furthermore, correlation analysis enabled the effect of anthropometric variables and years of playing experience to be investigated, in addition to the effect of HAE mechanisms and neck strength on HAE magnitude.

At baseline, positional disparity in anthropometric variables were limited, characteristic of women's rugby players. This is attributed to low experience levels, limited positional specificity and inadequate development pathways which prevent clear data trends from arising. When individually assessed, no HAE mechanism, playing position, playing experience or anthropometric variables, excluding standing height, had a significant effect on HAE magnitude. It is recommended that future analysis investigate how a combination of factors may predispose individuals to experiencing greater HAE magnitudes.

Within this female cohort, differences in isometric neck strength and HAE telemetry data were identified compared to previous male-centred studies. These data provide an example of just one area of rugby where sex differences are important. Females are not scaled down versions of men and therefore necessitate research rather than speculation and presumption. Collectively, the findings of this thesis highlight the importance of conducting further sex-disaggregated research in rugby, and do not support the generalisation of male-derived data to female players.

Bibliography

Aboitiz, F., Scheibel, A. B., Fisher, R. S., & Zaidel, E. (1992). Fiber composition of the human corpus callosum. *Brain Research*, *598*(1–2), 143–153. https://doi.org/10.1016/0006-8993(92)90178-C

Abrahams, S., Mc Fie, S., Patricios, J., Suter, J., September, A. V., & Posthumus, M. (2019). Toxic tau: The TAU gene polymorphisms associate with concussion history in rugby union players. *Journal of Science and Medicine in Sport*, *22*(1), 22–28. https://doi.org/10.1016/j.jsams.2018.06.012

Abrahams, S., McFie, S., Patricios, J., Posthumus, M., & September, A. V. (2014). Risk factors for sports concussion: An evidence-based systematic review. *British Journal of Sports Medicine*, *48*(2), 91–97. https://doi.org/10.1136/bjsports-2013-092734

Agel, J., & Harvey, E. J. (2010). A 7-year review of men's and women's ice hockey injuries in the NCAA. *Canadian Journal of Surgery*, *53*(5), 319–323.

Alexander, D. C., Hubbard, P. L., Hall, M. G., Moore, E. A., Ptito, M., Parker, G. J. M., & Dyrby, T. B. (2010). Orientationally invariant indices of axon diameter and density from diffusion MRI. *NeuroImage*, *52*(4), 1374–1389. https://doi.org/10.1016/j.neuroimage.2010.05.043

Almosnino, S., Pelland, L., Pedlow, S. V, & Stevenson, J. M. (2009). Between-day reliability of electromechanical delay of selected neck muscles during performance of maximal isometric efforts. *BMC Sports Science, Medicine and Rehabilitation*, *1*(1), 453–458. https://doi.org/10.1186/1758-2555-1-22

Argus, C. K., Gill, N., Keogh, J., Hopkins, W. G., & Beaven, C. M. (2010). Effects of a short-term pre-season training programme on the body composition and anaerobic performance of professional rugby union players. *Journal of Sports Sciences*, *28*(6), 679–686. https://doi.org/10.1080/02640411003645695

Ashall, A., Dobbin, N., & Thorpe, C. (2021). Physical Therapy in Sport The concurrent validity and intrarater reliability of a hand-held dynamometer for the assessment of neck strength in semi- professional rugby union players. *Physical Therapy in Sport*, *49*, 229–235. https://doi.org/10.1016/j.ptsp.2021.03.007

Attwood, M. J., Roberts, S. P., Trewartha, G., England, M. E., & Stokes, K. A. (2018). Efficacy of a movement control injury prevention programme in adult men's community rugby union: A cluster randomised controlled trial. *British Journal of Sports Medicine*, *52*(6), 368–374. https://doi.org/10.1136/bjsports-2017-098005

Austin, D., Gabbett, T., & Jenkins, D. (2011). The physical demands of Super 14 rugby union. *Journal of Science and Medicine in Sport*, *14*(3), 259–263. https://doi.org/10.1016/j.jsams.2011.01.003

Avila, J., Lucas, J. J., Pérez, M., & Hernández, F. (2004). Role of Tau Protein in Both Physiological and Pathological Conditions. *Physiological Reviews*, *84*(2), 361–384. https://doi.org/10.1152/physrev.00024.2003

Bailes, J., Turner, R., Lucke-Wold, B., Patel, V., & Lee, J. (2015). Chronic traumatic encephalopathy: Is it real? The relationship between neurotrauma and neurodegeneration. *Neurosurgery*, *62*(October 2017), 15–24. https://doi.org/10.1227/NEU.0000000000000811

Barbic, D., Pater, J., & Brison, R. (2005). Comparison of Mouth Guard Designs and Concussion Prevention in Contact Sports: A Multicenter Randomized Controlled Trial. *Clinical Journal of Sport Medicine*, *15*(5), 294–298.

Barrett, M., McLoughlin, T., Gallagher, K., Gatherer, D., Parratt, M., Perera, J., & Briggs, T. (2015). Effectiveness of a tailored neck training program on neck strength, movement, and fatigue in under-19 male rugby players: a randomized controlled pilot study. *Open Access Journal of Sports Medicine*, 137. https://doi.org/10.2147/oajsm.s74622

Barrios, P., Martin-Biggers, J., Quick, V., & Byrd-Bredbenner, C. (2016). Reliability and criterion validity of self-measured waist, hip, and neck circumferences. *BMC Medical Research Methodology*, *16*(1), 1–12. https://doi.org/10.1186/s12874-016-0150-2

Bartsch, A., Samorezov, S., Benzel, E., Miele, V., & Brett, D. (2014). Validation of an "Intelligent Mouthguard" Single Event Head Impact Dosimeter. *Stapp Car Crash Journal*, *58*(November), 1–27.

Bashir, R. (2020). Rugby: Artificial Pitch vs. Natural Grass. Retrieved September 17, 2020, from LWOS website: https://lastwordonsports.com/rugby/2020/04/20/rugby-artificial-pitch-vs-natural-grass/

Bathgate, A., Best, J. P., Craig, G., & Jamieson, M. (2002). A prospective study of injuries to elite Australian rugby union players. *British Journal of Sports Medicine*, *36*(4), 265–269. https://doi.org/10.1136/bjsm.36.4.265

Baumann, E. (2013). *A Scrum of Their Own: Why women play rugby, and how team culture affects player participation with the American university women's rugby football club*. Retrieved from http://dra.american.edu/islandora/object/1213capstones%3A73/datastream/PDF/view

Bazarian, J. J., & Atabaki, S. (2001). *Predicting Postconcussion Syndrome after Minor Traumatic Brain Injury*.

Belkhiria, C., De Marco, G., & Driss, T. (2018). Effects of verbal encouragement on force and electromyographic activations during exercise. *Journal of Sports Med Phys Fitness*, *58*(5), 750–757. https://doi.org/10.23736/S0022-4707.17.07282-6

Ben-Noun, L. L., Sohar, E., & Laor, A. (2001). Neck circumference as a simple screening measure for identifying overweight and obese patients. *Obesity Research*, *9*(8), 470–477. https://doi.org/10.1038/oby.2001.61

Benedict, P. A., Baner, N. V., Harrold, G. K., Moehringer, N., Hasanaj, L., Serrano, L. P., … Balcer, L. J. (2015). Gender and age predict outcomes of cognitive, balance and vision testing in a multidisciplinary concussion center. *Journal of the Neurological Sciences*, *353*(1–2), 111–115. https://doi.org/10.1016/j.jns.2015.04.029

Best, J. P., McIntosh, A., & Savage, T. N. (2005). Rugby World Cup 2003 injury surveillance project. *British Journal of Sports Medicine*, *39*(11), 812–817. https://doi.org/10.1136/bjsm.2004.016402

Bigham, K., & Hanlon, T. (2020). *Evaluating the Effect of Neck Strength on Concussions*. (April).

Binboga, E., Tok, S., Catikkas, F., Guven, S., & Dane, S. (2013). The effects of verbal encouragement and conscientiousness on maximal voluntary contraction of the triceps surae muscle in elite athletes. *Journal of Sports Sciences*, *31*(9), 982–988. https://doi.org/doi.org/10.1080/02640414.2012.758869

Bloom, G. A., Loughead, T. M., Shapcott, E. J. B., Johnston, K. M., & Delaney, J. S. (2008). The prevalence and recovery of concussed male and female collegiate athletes. *European Journal of Sport Science*, *8*(5), 295–303. https://doi.org/10.1080/17461390802251836

Boffano, P., Boffano, M., Gallesio, C., Roccia, F., Cignetti, R., & Piana, R. (2011). Rugby players' awareness of concussion. *Journal of Craniofacial Surgery*, *22*(6), 2053–2056. https://doi.org/10.1097/SCS.0b013e318231988d

Bogoslovsky, T., Wilson, D., Chen, Y., Hanlon, D., Gill, J., Jeromin, A., … Diaz-Arrastia, R. (2017). Increases of plasma levels of glial fibrillary acidic protein, tau, and amyloid β up to 90 days after traumatic brain injury. *Journal of Neurotrauma*, *34*(1), 66–73. https://doi.org/10.1089/neu.2015.4333

Borg, J., Holm, L., Cassidy, J. D., Peloso, P. M., Carroll, L. J., von Holst, H., & Ericson, K.

(2004). Diagnostic procedures in mild traumatic brain injury: Results of the WHO Collaborating Centre Task Force on Mild Traumatic Brain Injury. *Journal of Rehabilitation Medicine, Supplement*, pp. 61–75. https://doi.org/10.1080/16501960410023822

Bose, D., Segui-Gomez, M., & Crandall, J. R. (2011). Vulnerability of female drivers involved in motor vehicle crashes: An analysis of US population at risk. *American Journal of Public Health*, *101*(12), 2368–2373. https://doi.org/10.2105/AJPH.2011.300275

Brain Trauma Foundation. (2020). Brain Trauma Foundation. Retrieved February 15, 2020, from Traumatic Brain Injury website: https://www.braintrauma.org/faq

Bramblett, G., Goedert, M., Jakes, R., Merrick, S., Trojanowski, J., & Lee, V. (1993). Abnormal tau phosphorylation at Ser396 in Alzheimer's disease recapitulates development and contributes to reduced microtubule binding. *Neurone*, *10*(6), 1089–1099.

Brand, S. (2019). *Position-specific characteristics for elite adolescent male rugby players in the North West province*.

Broglio, S., Schnebel, B., Sosnoff, J., Shin, S., Feng, X., He, X., & Zimmerman, J. (2010). The biomechanical properties of concussion in high school football. *Medicine and Science in Sports and Exercise*, *42*(11), 2064–2071. Retrieved from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2943536/

Brolin, K., Hedenstierna, S., Halldin, P., Bass, C. R., & Alem, N. (2008). The importance of muscle tension on the outcome of impacts with a major vertical component. *Journal of Crashworthiness*, *13*(5), 487–498. https://doi.org/10.1080/13588260802215510

Brooks, J. H. M., & Kemp, S. P. T. (2011). Injury-prevention priorities according to playing position in professional rugby union players. *British Journal of Sports Medicine*, *45*(10), 765–775. https://doi.org/10.1136/bjsm.2009.066985

Brooks, J, Fuller, C., Kemp, S., & Reddin, D. (2005). A prospective study of injuries and training amongst the England 2003 Rugby World Cup squad. *British Journal of Sports Medicine*, *39*(5), 288–293. https://doi.org/10.1136/bjsm.2004.013391

Brooks, John, & Kemp, S. (2008, January 1). Recent Trends in Rugby Union Injuries. *Clinics in Sports Medicine*, Vol. 27, pp. 51–73. https://doi.org/10.1016/j.csm.2007.09.001

Broshek, D. K., Kaushik, T., Freeman, J. R., Erlanger, D., Webbe, F., & Barth, J. T. (2005). Sex differences in outcome following sports-related concussion. *Journal of Neurosurgery*, *102*(5), 856–863. https://doi.org/10.3171/jns.2005.102.5.0856

Brown, D., Elsass, J., Miller, A., Reed, L., & Reneker, J. (2015). Differences in Symptom Reporting Between Males and Females at Baseline and After a Sports-Related Concussion: A Systematic Review and Meta-Analysis. *Sports Medicine*, *45*(7), 1027–1040. https://doi.org/10.1007/s40279-015-0335-6

Burger, N., Lambert, M. I., Viljoen, W., Brown, J. C., Readhead, C., Den Hollander, S., & Hendricks, S. (2017). Mechanisms and Factors Associated with Tackle-Related Injuries in South African Youth Rugby Union Players. *American Journal of Sports Medicine*, *45*(2), 278–285. https://doi.org/10.1177/0363546516677548

Bussey, M., McLean, M., Pinfold, J., Anderson, N., Kiely, R., Romanchuk, J., & Salmon, D. (2019). History of concussion is associated with higher head acceleration and reduced cervical muscle activity during simulated rugby tackle: An exploratory study. *Physical Therapy in Sport*, *37*, 105–112. https://doi.org/10.1016/j.ptsp.2019.03.012

Cahill, N., Lamb, K., Worsfold, P., Headey, R., & Murray, S. (2013). The movement characteristics of English Premiership rugby union players. *Journal of Sports Sciences*, *31*(3), 229–237. https://doi.org/10.1080/02640414.2012.727456

Camarillo, D., Shull, P., Mattson, J., Shultz, R., & Garza, D. (2013). An instrumented mouthguard for measuring linear and angular head impact kinematics in american football. *Annals of Biomedical Engineering*, *41*(9), 1939–1949. https://doi.org/10.1007/s10439-013-0801-y

Carey, L., Stanwell, P., Terry, D., McIntosh, A., Caswell, S., Iverson, G., & Gardner, A. (2019). Verifying Head Impacts Recorded by a Wearable Sensor using Video Footage in Rugby League: a Preliminary Study. *Sports Medicine - Open*, *5*(1). https://doi.org/10.1186/s40798-019-0182-3

Carmichael, J., Staton, E., Blatchford, P., & Stevens-Lapsley, J. (2019). EPIDEMIOLOGY of NECK INJURIES ACCOMPANYING SPORT CONCUSSIONS in YOUTH OVER a 13-YEAR PERIOD IN a COMMUNITY-BASED HEALTHCARE SYSTEM. *International Journal of Sports Physical Therapy*, *14*(3), 334–344. https://doi.org/10.26603/ijspt20190334

Carmont, M., Kelberine, F., & Lester, C. (2020). Rugby. *Injury and Health Risk Management in Sports*, 479–484.

Cassidy, J. D., Carroll, L. J., Peloso, P. M., Borg, J., von Holst, H., Holm, L., … Coronado, V. G. (2004). Incidence, risk factors and prevention of mild traumatic brain injury: Results of the WHO Collaborating Centre Task Force on Mild Traumatic Brain Injury. *Journal of Rehabilitation Medicine, Supplement*, (43), 28–60. https://doi.org/10.1080/16501960410023732

Catenaccio, E. (2017). *Characterization of Neck Strength in Healthy Young Adults* (pp. 884–891). pp. 884–891. Retrieved from chrome-extension://dagcmkpagjlhakfdhnbomgmjdpkdklff/enhanced-reader.html?openApp&pdf=https%3A%2F%2Fwww.ncbi.nlm.nih.gov%2Fpmc%2Farticles%2FPMC5545075%2Fpdf%2Fnihms849759.pdf

Chalmers, D., Samaranayaka, A., Gulliver, P., & McNoe, B. (2011). Risk factors for injury in rugby union football in New Zealand: A cohort study. *British Journal of Sports Medicine*, *46*(2), 95–102. https://doi.org/10.1136/bjsports-2011-090272

Chamard, E., Lefebvre, G., Lassonde, M., & Theoret, H. (2016). Long-Term Abnormalities in the Corpus Callosum of Female Concussed Athletes. *Journal of Neurotrauma*, *33*(13), 1220–1226. https://doi.org/10.1089/neu.2015.3948

Chancey, V. C., Nightingale, R. W., Van Ee, C. A., Knaub, K. E., & Myers, B. S. (2003). Improved Estimation of Human Neck Tensile Tolerance: Reducing the Range of Reported Tolerance Using Anthropometrically Correct Muscles and Optimized Physiologic Initial Conditions. *SAE Technical Papers*, *2003-Octob*(October), 1–19. https://doi.org/10.4271/2003-22-0008

Chavarro-Nieto, C., Beaven, M., Gill, N., & Hebert-Losier, K. (2021). Neck strength in Rugby Union players: a systematic review of the literature. In *The physician and sports medicine*. https://doi.org/10.1080/00913847.2021.1886574

Chu, M., Leberman, S., Howe, B., & Bachor, D. (2003). The Black Ferns: The Experienes of New Zealand's Elite Womens Rugby Players. *Journal of Sports Behaviour*, *26*(2), 111–122. Retrieved from https://web.b.ebscohost.com/abstract?direct=true&profile=ehost&scope=site&authtype=crawler&jrnl=01627341&AN=9691168&h=AZkToT2d6Pr2dg0Ow7Y8Jfzs4ZlfDrlUpQVMK0NHxWQy2FBCaEizweVsV%2F9Mw7P4HbF7c4o3svEMUPFxeh%2F8%2Bw%3D%3D&crl=c&resultNs=AdminWebAuth&resultLoca

Cirillo, D., Catuara-Solarz, S., Morey, C., Guney, E., Subirats, L., Mellino, S., … Mavridis, N. (2020). Sex and gender differences and biases in artificial intelligence for biomedicine and healthcare. *Npj Digital Medicine*, *3*(1), 1–11. https://doi.org/10.1038/s41746-020-0288-5

Clarke, A. (2016). *Improving the Physical Preparation and Devel opment of Women's Rugby Sevens P layers*.

Collins, C., Fletcher, E., Fields, S., Kluchurosky, L., Rohrkemper, M. K., Comstock, D., & Cantu, R. (2014). Neck strength: A protective factor reducing risk for concussion in high school sports. *The Journal of Primary Prevention*, *35*, 309–319.

Colvin, A. C., Mullen, J., Lovell, M. R., West, R. V., Collins, M. W., & Groh, M. (2009). The role of concussion history and gender in recovery from soccer-related concussion. *American Journal of Sports Medicine*, *37*(9), 1699–1704. https://doi.org/10.1177/0363546509332497

Colwell, R., Bear, A., & Helman, A. (2020). The National Academies of Sciences, Engineering, and Medicine 2020. In mathematics and medicine (STEMM) Committee of increasing the number of women in sceince, technology (Ed.), *Promising practices for addressing the underrepresentation of women in science, engineering and medicine: opening doors*. Retrieved from https://books.google.co.uk/books?hl=en&lr=&id=5j3ZDwAAQBAJ&oi=fnd&pg=PR1&dq=females+underrepresented+in+medical+science+research&ots=97a7vccZMN&sig=-hWMyGLoozHLUnQkgOk7pXjKSrI&redir_esc=y#v=onepage&q=females underrepresented in medical science research&f=

Conley, M., Stone, M., Nimmons, M., & Dudley, G. (1997). Specificity of resistance training responses in neck muscle size and strength. *European Journal of Applied Physiology and Occupational Physiology*, *75*(5), 443–448. https://doi.org/10.1007/s004210050186

Costello, J. T., Bieuzen, F., & Bleakley, C. M. (2014). Where are all the female participants in Sports and Exercise Medicine research? *European Journal of Sport Science*, *14*(8), 847–851. https://doi.org/10.1080/17461391.2014.911354

Coughlan, G. F., Fullen, B. M., & McCarthy, C. (2014). A national survey of clubs medical personnel, facilities and protocols in Irish Rugby Union. *Irish Journal of Medical Science*, *183*(1), 39–45. https://doi.org/10.1007/s11845-013-0968-0

Coutts, A., Murphy, A., & Dascombe, B. (2004). Effect of direct supervision of a stregnth coach on measures of muscular strength and power in young rugby league players. *Journal of Strength and Conditioning Research*, *18*(2), 316–323. Retrieved from https://opus.lib.uts.edu.au/bitstream/10453/9724/1/2003001284OK.pdf

Covassin, T., Elbin, R. J., Harris, W., Parker, T., & Kontos, A. (2012). The role of age and sex in symptoms, neurocognitive performance, and postural stability in athletes after concussion. *American Journal of Sports Medicine*, *40*(6), 1303–1312. https://doi.org/10.1177/0363546512444554

Covassin, T., Moran, R., & Elbin, R. J. (2016). Sex differences in reported concussion injury rates and time loss from participation: An update of the national collegiate athletic association injury surveillance program from 2004-2005 through 2008-2009. *Journal of Athletic Training*, *51*(3), 189–194. https://doi.org/10.4085/1062-6050-51.3.05

Covassin, T., Swanik, C., Sachs, M., Kendrick, Z., Schatz, P., Zillmer, E., & Kaminaris, C. (2006). Sex differences in baseline neuropsychological function and concussion symptoms of collegiate athletes. *British Journal of Sports Medicine*, *40*(11), 923–927. https://doi.org/10.1136/bjsm.2006.029496

Covassin, T., Swanikt, C. B., & Sachs, M. L. (2003). Sex Differences and the Incidence of Concussions among Collegiate Athletes. *Journal of Athletic Training*, *38*(3), 238–244.

Cramer, D., & Howitt, D. (2004). The SAGE dictionary of statistics: A practical resouce for students in social science. In *Sage Publications*. London.

Cross, M., Tucker, R., Raftery, M., Hester, B., Williams, S., Stokes, K., … Kemp, S. (2019). Tackling concussion in professional rugby union: A case-control study of tackle-based risk factors and recommendations for primary prevention. *British Journal of Sports Medicine*, *53*(16), 1021–1025. https://doi.org/10.1136/bjsports-2017-097912

Cusimano, M., Cho, N., Amin, K., Shirazi, M., McFaull, S., Do, M., … Russell, K. (2013).

Mechanisms of Team-Sport-Related Brain Injuries in Children 5 to 19 Years Old: Opportunities for Prevention. *PLoS ONE*, *8*(3), 1–8. https://doi.org/10.1371/journal.pone.0058868

Daneshvar, D. H., Baugh, C. M., Nowinski, C. J., McKee, A. C., Stern, R. A., & Cantu, R. C. (2011). Helmets and Mouth Guards: The Role of Personal Equipment in Preventing Sport-Related Concussions. *Clinics in Sports Medicine*, *30*(1), 145–163. https://doi.org/10.1016/j.csm.2010.09.006

Davidow, D., Redman, M., Lambert, M., Burger, N., Smith, M., Jones, B., & Hendricks, S. (2020). The effect of physical fatigue on tackling technique in rugby union. *Journal of Science and Medicine in Sport*. Retrieved from https://reader.elsevier.com/reader/sd/pii/S1440244019314707?token=CC77F0CAD45DAABFD48C591B848C44DF6E06BCD899F18535E3CAF03CF17CA504673DCAE33E55D3562DAC121F112F4B1B

Day, L. (2020). Rugby concussion: Swansea University study into protecting women. Retrieved June 25, 2020, from BBC news website: https://www.bbc.co.uk/news/uk-wales-51434749

De Lacoste-Utamsing, C., & Holloway, R. L. (1982). Sexual dimorphism in the human corpus callosum. *Science*, *216*(4553), 1431–1432. https://doi.org/10.1126/science.7089533

Dennison, C., Macri, E., & Cripton, P. (2012). Mechanisms of cervical spine injury in rugby union: Is it premature to abandon hyperflexion as the main mechanism underpinning injury? *British Journal of Sports Medicine*, *46*(8), 545–549. https://doi.org/10.1136/bjsports-2012-091257

Dezman, Z. D. W., Ledet, E. H., & Kerr, H. A. (2013). Neck Strength Imbalance Correlates With Increased Head Acceleration in Soccer Heading. *Sports Health*, *5*(4), 320–326. https://doi.org/10.1177/1941738113480935

Dick, R. W. (2009). Is there a gender difference in concussion incidence and outcomes? *British Journal of Sports Medicine*, *43*(SUPPL. 1), 46–50. https://doi.org/10.1136/bjsm.2009.058172

Dollé, J. P., Jaye, A., Anderson, S., Ahmadzadeh, H., Shenoy, V., & Smith, D. (2018). Newfound sex differences in axonal structure underlie differential outcomes from in vitro traumatic axonal injury. *Experimental Neurology*, *300*, 121–134. https://doi.org/10.1016/j.expneurol.2017.11.001

Donnelly, A. (2018). England's pro contracts will change women's rugby union for ever. Retrieved from The Guardian website: https://www.theguardian.com/sport/blog/2018/sep/18/england-pro-contracts-change-womens-rugby-union-for-ever

Dovey, C. (2016, April 9). The magnificent seven: rugby team's tilt for Rio glory. *The Sydney Morning Herald*. Retrieved from https://www.smh.com.au/lifestyle/the-magnificent-seven-rugby-teams-tilt-for-rio-glory-20160407-go0icd.html

Dubois, R., Paillard, T., Lyons, M., McGrath, D., Maurelli, O., & Prioux, J. (2017). Running and Metabolic Demands of Elite Rugby Union Assessd Using Traditional, Metabolic Power, and Heart Rate Monitoring MEhtods. *Journal of Sports Science Medicine*, *16*(1), 84–92. Retrieved from https://pubmed.ncbi.nlm.nih.gov/28344455/

Duthie, G., Pyne, D., & Hooper, S. (2003). Applied Physiology and Game Analysis of Rugby Union. In *Sports Med* (Vol. 33).

Dvir, Z., & Prushansky, T. (2008). Cervical muscles strength testing: methods and clinical implications. *Journal of Manipulative and Phsyiological Therapeutics*, *31*(7), 518–524. https://doi.org/10.1002/9780470693766.ch1

Eaves, S., & Hughes, M. (2003). Patterns of play of international rugby union teams before and after the introduction of professional status. *International Journal of Performance*

Analysis in Sport, *3*(2), 103–111.

Echemendia, R. J., Meeuwisse, W., McCrory, P., Davis, G. A., Putukian, M., Leddy, J., … Herring, S. (2017). The Sport Concussion Assessment Tool 5th Edition (SCAT5): Background and rationale. *British Journal of Sports Medicine*, *51*(11), 848–850. https://doi.org/10.1136/bjsports-2017-097506

Eckersley, C., Nightingale, R., Luck, J., & Bass, C. (2019). The role of cervical muscles in mitigating concussion. *Journal of Science and Medicine in Sport*, *22*(6), 667–671. https://doi.org/10.1016/j.jsams.2019.01.009

Eckner, J., Goshtasbi, A., Curtis, K., Kapshai, A., Myyra, E., Franco, L., … Ashton-Miller, J. (2018). Feasibility and Effect of Cervical Resistance Training on Head Kinematics in Youth Athletes: A Pilot Study. *American Journal of Physical Medicine and Rehabilitation*, *97*(4), 292–297. https://doi.org/10.1016/j.physbeh.2017.03.040

Edmondston, S., Wallumrød, M., MacLéid, F., Kvamme, L., Joebges, S., & Brabham, G. (2008). Reliability of Isometric Muscle Endurance Tests in Subjects With Postural Neck Pain. *Journal of Manipulative and Physiological Therapeutics*, *31*(5), 348–354. https://doi.org/10.1016/j.jmpt.2008.04.010

El-Menyar, A., El-Hennawy, H., Al-Thani, H., Asim, M., Abdelrahman, H., Zarour, A., … Latifi, R. (2014). Traumatic injury among females: Does gender matter? *Journal of Trauma Management and Outcomes*, *8*(1), 1–8. https://doi.org/10.1186/1752-2897-8-8

Emmonds, S., Heyward, O., & Jones, B. (2019). The Challenge of Applying and Undertaking Research in Female Sport. *Sports Medicine - Open*, *5*(1). https://doi.org/10.1186/s40798-019-0224-x

England Rugby. (2019). Record breaking numbers for global game. https://doi.org/https://www.englandrugby.com/news/article/record-breaking-numbers-for-global-game

Falla, D. (2004). Unravelling the complexity of muscle impairment in chronic neck pain. *Man Ther*, *9*(3), 125–133. https://doi.org/10.1016/j.math.2004.05.003

Feldman, S., Ammar, W., Lo, K., Trepman, E., Van Zuylen, M., & Etzioni, O. (2019). Quantifying Sex Bias in Clinical Studies at Scale with Automated Data Extraction. *JAMA Network Open*, *2*(7), 1–14. https://doi.org/10.1001/jamanetworkopen.2019.6700

Ferretti, M. T., Iulita, M. F., Cavedo, E., Chiesa, P. A., Dimech, A. S., Chadha, A. S., … Hampel, H. (2018). Sex differences in Alzheimer disease — The gateway to precision medicine. *Nature Reviews Neurology*, *14*(8), 457–469. https://doi.org/10.1038/s41582-018-0032-9

Finch, C., McIntosh, A., & McCrory, P. (2001). What do under 15 year old schoolboy rugby union players think about protective headgear? *British Journal of Sports Medicine*, *35*(2), 89–94. https://doi.org/10.1136/bjsm.35.2.89

Findlay, R. J., Macrae, E. H. R., Whyte, I. Y., Easton, C., & Forrest, L. J. (2020). How the menstrual cycle and menstruation affect sporting performance: Experiences and perceptions of elite female rugby players. *British Journal of Sports Medicine*, 1–7. https://doi.org/10.1136/bjsports-2019-101486

Frommer, L. J., Gurka, K. K., Cross, K. M., Ingersoll, C. D., Comstock, R. D., & Saliba, S. A. (2011). Sex differences in concussion symptoms of high school athletes. *Journal of Athletic Training*, *46*(1), 76–84. https://doi.org/10.4085/1062-6050-46.1.76

Fuller, C., Ashton, T., Brooks, J., Cancea, R., Hall, J., & Kemp, S. (2010). Injury risks associated with tackling in rugby union. *British Journal of Sports Medicine*, *44*(3), 159–167. https://doi.org/10.1136/bjsm.2008.050864

Fuller, C., Brooks, J., Cancea, R., Hall, J., & Kemp, S. (2007). Contact events in rugby union and their propensity to cause injury. *British Journal of Sports Medicine*, *41*(12), 862–867. https://doi.org/10.1136/bjsm.2007.037499

Fuller, C., Brooks, J., & Kemp, S. (2007). Spinal injuries in professional rugby union: A prospective cohort study. *Clinical Journal of Sport Medicine*, *17*(1), 10–16. https://doi.org/10.1097/JSM.0b013e31802e9c28

Fuller, C. W., Taylor, A., Kemp, S. P. T., & Raftery, M. (2017). Rugby World Cup 2015: World Rugby injury surveillance study. *British Journal of Sports Medicine*, *51*(1), 51–57. https://doi.org/10.1136/bjsports-2016-096275

Gabb, N. (2018). *Epidemiology of injury in elite level female rugby union players in England*.

Gadd, C. (1966). Use of a Weighted-Impulse Criterion for Estimating Injury Hazard. *SAE Technical Papers*, *660793*. https://doi.org/https://doi.org/10.4271/660793

Gardner, A. J., Iverson, G. L., Williams, W. H., Baker, S., & Stanwell, P. (2014, November 25). A systematic review and meta-analysis of concussion in Rugby Union. *Sports Medicine*, Vol. 44, pp. 1717–1731. https://doi.org/10.1007/s40279-014-0233-3

Gardner, A., Quarrie, K., & Iverson, G. (2019). The epidemiology of sport-related concussion: What the rehabilitation clinician needs to know. *Journal of Orthopaedic and Sports Physical Therapy*, *49*(11), 768–778. https://doi.org/10.2519/jospt.2019.9105

Gardner, A., Shores, E. A., & Batchelor, J. (2010). Reduced processing speed in rugby union players reporting three or more previous concussions. *Archives of Clinical Neuropsychology*, *25*(3), 174–181. https://doi.org/10.1093/arclin/acq007

Garraway, W., Lee, A., Hutton, S., Russell, E., & Macleod, D. (2000). Impact of professionalism on injuries in rugby union. *British Journal of Sports Medicine*, *34*(5), 348–351. https://doi.org/10.1136/bjsm.34.5.348

Gavett, B. E., Stern, R. A., & McKee, A. C. (2011). Chronic Traumatic Encephalopathy: A Potential Late Effect of Sport-Related Concussive and Subconcussive Head Trauma. *Clinics in Sports Medicine*, *30*(1), 179–188. https://doi.org/10.1016/j.csm.2010.09.007

Gennarelli, T., Pintar, F., Yoganandan, N., Sinson, G., Beuse, N., Chan, B., & Morgan, R. (2002). Head injuries to nearside occupants in lateral impacts: epidemiological and full-scale crash test analyses. *International Research Council on Biomechanics of Injury*, *30*(11). Retrieved from https://www.safetylit.org/citations/index.php?fuseaction=citations.viewdetails&citationIds%5B%5D=citjournalarticle_247548_12

Greenwald, R. M., & Ph, D. (2008). *H Ead I Mpact S Everity M Easures for E Valuating*. *62*(4), 789–798. https://doi.org/10.1227/01.NEU.0000311244.05104.96

Greybe, D., Jones, C., Brown, M. R., & Williams, E. (2020). Comparison of head impact measurements via an instrumented mouthguard and an anthropometric testing device. *Sports Engineering*, *23*(1). https://doi.org/10.1007/s12283-020-00324-z

Gurdjian, E., Roberts, V., & Thomas, L. (1966). Tolerance curves of acceleration and intracranial pressure and protective index in experimental head injury. *The Journal of Trauma*, *6*(5). https://doi.org/10.1097/00005373-196609000-00005.

Guskiewicz, K. M., Marshall, S. W., Bailes, J., Mccrea, M., Harding, H. P., Matthews, A., … Cantu, R. C. (2007). Recurrent concussion and risk of depression in retired professional football players. *Medicine and Science in Sports and Exercise*, *39*(6), 903–909. https://doi.org/10.1249/mss.0b013e3180383da5

Haarbauer-Krupa, J., Arbogast, K. B., Metzger, K. B., Greenspan, A. I., Kessler, R., Curry, A. E., … Master, C. L. (2018). Variations in Mechanisms of Injury for Children with Concussion. *Journal of Pediatrics*, *197*(March 2017), 241-248.e1. https://doi.org/10.1016/j.jpeds.2018.01.075

Hagmann, P., Cammoun, L., Gigandet, X., Meuli, R., Honey, C. J., Van Wedeen, J., & Sporns, O. (2008). Mapping the structural core of human cerebral cortex. *PLoS Biology*, *6*(7), 1479–1493. https://doi.org/10.1371/journal.pbio.0060159

Hall, T., Morissette, M., Cordingley, D., & Leiter, J. (2017). Reliability of a Novel Technique for the Measurement of Neck Strength. *International Journal of Athletic Therapy and Training*. https://doi.org/https://doi.org/10.1123/ijatt.2016-0070

Hamilton, D. F., Gatherer, D., Maclean, J. G. B., Hutchison, J. D., Nutton, R. W., & Simpson, A. H. R. W. (2012). Age-related differences in the neck strength of adolescent rugby players: A cross-sectional cohort study of Scottish schoolchildren. *Bone & Joint Research*, *1*(7), 152–157. https://doi.org/10.1302/2046-3758.17.2000079

Hamilton, D, Gatherer, D., Robson, J., Graham, N., Rennie, N., MacLean, J., & Simpson, A. (2014). Comparative cervical profiles of adult and under-18 front-row rugby players: Implications for playing policy. *BMJ Open*, *4*(5), 1–7. https://doi.org/10.1136/bmjopen-2014-004975

Hamilton, David, & Gatherer, D. (2014). Cervical isometric strength and range of motion of elite rugby union players: A cohort study. *BMC Sports Science, Medicine and Rehabilitation*, *6*(1), 1–6. https://doi.org/10.1186/2052-1847-6-32

Hamlin, M., Deuchrass, R., Elliot, C., Raj, T., & Promkeaw, D. (2020). Effect of a 6-week exercise intervention for improved neck muscle strength in amateur male rugby union players. *The Journal of Sport and Exercise Science*, *4*(1), 33–39. https://doi.org/10.36905/jses.2020.01.05

Hanney, W., & Kolber, M. (2007). Improving muscle performance of the deep neck flexors. *Strength and Conditioning Journal*, *29*(3), 78–83. https://doi.org/10.1519/00126548-200706000-00012

Harmon, K., Drezner, J., Gammons, M., Guskierwicz, K., Halstead, M., Herring, S., … Roverts, W. (2013). American Medical Society for Sports Medicine Position Statement: Concussion in Sport. *Clinical Journal of Sport Medicine*, *23*(1), 1–18.

Harris, K., Heer, D., Roy, T., Santos, D., Whitman, J., & Wainner, R. (2005). Reliability of a measurement of neck flexor muscle endurance. *Physical Therapy*, *85*(12), 1349–1355. https://doi.org/10.1093/ptj/85.12.1349

Hedenstierna, S. (2008). *3D Finite Element Modeling of Cervical Musculature and its Effect on Neck Injury Prevention*. https://doi.org/ISSN: 1653-3836

Hendricks, S., Karpul, D., & Lambert, M. (2014). Momentum and kinetic energy before the tackle in rugby union. *Journal of Sports Science and Medicine*, *13*(3), 557–563.

Hene, N., Bassett, S., & Andrews, B. (2011). Physical fitness of elite female Rugby Union players. *African Journal for Physical, Health Education, Recreation and Dance*, *17*(3). https://doi.org/10.4314/ajpherd.v17i3.68066

Herdem, S. R., & Kaynak, K. (2019). Investigating the effects of different strength training methods on body composition. *International Journal of Applies Exercise Physiology*, *8*(4), 37–46.

Hernandez, F., Shull, P., & Camarillo, D. (2015). Evaluation of a laboratory model of human head impact biomechanics. *Journal of Biomechanics*, *48*(12), 3469–3477. https://doi.org/https://doi.org/10.1016/j.jbiomech.2015.05.034

Hernandez, F., Wu, L., Yip, M., Laksari, K., Hoffman, A., Lopez, J., … Camarillo, D. (2016). Six Degree of Freedom Measurements of Human Mild Traumatic Brain Injury. *Biomed Eng*, *44*(3), 1918–1934. https://doi.org/10.1007/s10439-014-1212-4

Hilton, E. N., & Lundberg, T. R. (2020). *Transgender Women in The Female Category of Sport: Is the Male Performance Advantage Removed by Testosterone Suppression?* (May), 2020. https://doi.org/10.20944/PREPRINTS202005.0226.V1

Hind, K., Konerth, N., Entwistle, I., Theadom, A., Lewis, G., King, D., … 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*, (0123456789). https://doi.org/10.1007/s40279-020-01310-y

Hislop, M. D., Stokes, K. A., Williams, S., McKay, C. D., England, M. E., Kemp, S. P. T., &

Trewartha, G. (2017). Reducing musculoskeletal injury and concussion risk in schoolboy rugby players with a pre-activity movement control exercise programme: A cluster randomised controlled trial. *British Journal of Sports Medicine*, *51*(15), 1140–1146. https://doi.org/10.1136/bjsports-2016-097434

Hoel, A., Kayssi, A., Brahmanandam, S., Belkin, M., Conte, M., & Nguyen, L. (2009). Under-representation of women and ethnic minorities in vascular surgery randomized controlled trials. *Journal of Vascular Surgery*, *50*(2), 349–354. https://doi.org/10.1016/j.jvs.2009.01.012

Holdcroft, A. (2007). Gender bias in research: How does it affect evidence based medicine? *Journal of the Royal Society of Medicine*, *100*(1), 2–3. https://doi.org/10.1258/jrsm.100.1.2

Hollander, S. Den, Ponce, C., Lambert, M., Jones, B., & Hendricks, S. (2021). Tackle and ruck technical proficiency in rugby union and rugby league: A systematic scoping review. *International Journal of Sports Science and Coaching*, *16*(2), 421–434. https://doi.org/10.1177/1747954120976943

Hollis, S., Stevenson, M., McIntosh, A., Shores, E. A., & Finch, C. (2012). Compliance with return-to-play regulations following concussion in Australian schoolboy and community rugby union players. *British Journal of Sports Medicine*, *46*(10), 735–740. https://doi.org/10.1136/bjsm.2011.085332

Hon, K. L., Leung, A. K. C., & Torres, A. R. (2019). Concussion: A Global Perspective. *Seminars in Pediatric Neurology*, *30*, 117–127. https://doi.org/10.1016/j.spen.2019.03.017

Hrysomallis, C. (2016). Neck Muscular Strength, Training, Performance and Sport Injury Risk: A Review. *Sports Medicine*, *46*(8), 1111–1124. https://doi.org/10.1007/s40279-016-0490-4

Hume, P. A., Theadom, A., Lewis, G. N., Quarrie, K. L., Brown, S. R., Hill, R., & Marshall, S. W. (2016). A Comparison of Cognitive Function in Former Rugby Union Players Compared with Former Non-Contact-Sport Players and the Impact of Concussion History. *Sports Medicine*, 1–12. https://doi.org/10.1007/s40279-016-0608-8

Hutchinson, J., Kaiser, M., & Lankarani, H. (1998). The Head Injury Criterion (HIC) functional. *Applied Mathematics and Computation*, *96*(1), 1–16. https://doi.org/10.1016/S0096-3003(97)10106-0

IGEA. (2020). Spinal Anatomy.

Ingle, S. (2020). World Rugby criticised by dozens of academics for trans women ban. Retrieved September 18, 2020, from The Guardian website: https://www.theguardian.com/sport/2020/sep/01/world-rugby-criticised-by-dozens-of-academics-for-trans-women-ban

International Rugby Players. (2021). *Women's survey: Who's playing the game?*

IOC. (2016). Factsheet: Women in the Olympic Movement. *International Olympic Committee*, (January), 1–5.

IOC. (2020). Women in Sports Statistics - Female Athlete Participation. Retrieved December 5, 2020, from Women in sport website: https://www.olympic.org/women-in-sport/background/statistics

IRB. (2016). World Rugby Recognise and Remove concussion education completed by record numbers. Retrieved from World Rugby website: https://www.world.rugby/news/134498?lang=enIRU

Ivancic, P. (2012). Head-First Impact With Head Protrusion Causes Noncontiguous Injuries of the Cadaveric Cervical Spine. *Clinical Journal of Sport Medicine*, *22*(5), 390–396.

Iwata, A., Stys, P. K., Wolf, J. A., Chen, X. H., Taylor, A. G., Meaney, D. F., & Smith, D. H. (2004). Traumatic axonal injury induces proteolytic cleavage of the voltage-gated sodium channels modulated by tetrodotoxin and protease inhibitors. *Journal of Neuroscience*, *24*(19), 4605–4613. https://doi.org/10.1523/JNEUROSCI.0515-03.2004

Jakobsson, L., Norin, H., & Isaksson-Hellman, I. (2000). PARAMETERS INFLUENCING THE RISK OF AIS1 NECK INJURIES IN FRONTAL AND SIDE IMPACTS. *Science, Engineering, Medicine*, 235–247. Retrieved from https://trid.trb.org/view/715656

Jakoet, I., & Noakes, T. D. (n.d.). *SAMJ A high rate of injury during the 1995 Rugby World Cup*.

Janssen, M., Drevelle, X., Humbert, L., Skalli, W., & Castelein, R. (2009). Differences in male and female spino-pelvic alignment in asymptomatic young adults: A three-dimensional analysis using upright low-dose digital biplanar X-rays. *Spine*, *34*(23), 826–832. https://doi.org/10.1097/BRS.0b013e3181a9fd85

Jawabri, K., & Sharma, S. (2020). Physiology, Cerebral Cortex Functions. Retrieved from StatPearls (internet) website: https://www.ncbi.nlm.nih.gov/books/NBK538496/

Jefferson, G. (1919). Fracture of the atlas vertebra. Report of four cases, and a review of those previously recorded. *British Journal of Surgery*, *7*(27), 407–422.

Johnson, V. E., Stewart, W., & Smith, D. H. (2013). Axonal pathology in traumatic brain injury. *Experimental Neurology*, *246*, 35–43. https://doi.org/10.1016/j.expneurol.2012.01.013

Joncheray, H., & Tlili, H. (2017). *Are there still social barriers to women's rugby?*

Jones, B., Emmonds, S., Hind, K., Nicholson, G., Rutherford, Z., & Till, K. (2016). Physical qualities of international female rugby league players by playing position. *Journal of Strength and Conditioning Research*, *30*(5), 1333–1340. https://doi.org/10.1519/JSC.0000000000001225

Jones, L. (2019). Wales women return to Arms Park as six nations fixtures confirmed.

Jung, M. C., & Hallbeck, M. S. (2004). Quantification of the effects of instruction type, verbal encouragement, and visual feedback on static and peak handgrip strength. *International Journal of Industrial Ergonomics*, *34*(5), 367–374. https://doi.org/10.1016/j.ergon.2004.03.008

Kearney, P. E. (2017). Playing postion influences the relative age effect in senior rugby union. *Science and Sports*, *32*(2), 114–116. https://doi.org/10.1016/j.scispo.2016.06.009

Keet, K., Roy, J., & Henry, B. M. (2019). Reporting sex or gender in anatomical research: Which is appropriate? *Clinical Anatomy*, *32*(5), 697–698. https://doi.org/10.1002/ca.23375

Kemp, S., Hudson, Z., Brooks, J., & Fuller, C. (2008). In elite rugby union players, there is a high incidence (injuries/1000 hours play) of head injury (6.6) and concussion (4.1) in matches - tackling and being tackled head-on are the most common mechanisms of injury. *Clinical Journal of Sports Medicine*, *18*(3), 227–234. Retrieved from https://d1wqtxts1xzle7.cloudfront.net/50359222/The_epidemiology_of_head_injuries_in_Eng20161116-6445-w16rii.pdf?1479333187=&response-content-disposition=inline%3B+filename%3DThe_Epidemiology_of_Head_Injuries_in_Eng.pdf&Expires=1602775460&Signature=NcvalRQ

Kent, M. (2006). *The Oxford Dictionary of Sports Science & Medicine* (M. Kent, Ed.). Oxford University Press.

Kerr, H., Curtis, C., Micheli, L., Kocher, M., Zurakowski, D., Kemp, S., & Brooks, J. (2008). Collegiate rugby union injury patterns in New England: A prospective cohort study. *British Journal of Sports Medicine*, *42*(7), 595–603. https://doi.org/10.1136/bjsm.2007.035881

Kevin, G., & Brian, G. (2014). Effects of Neck Strength Training on Isometric Neck Strength in Rugby Union Players. *Clinical Journal of Sports Medicine*, *24*(6), 502–508.

Kieffer, E., Vaillancourt, C., Brolinson, P. G., & Rowson, S. (2020). Using in-mouth sensors to measure head kinematics in rugby. *IRCOBI Conference*, 846–858.

King, A. I., Yang, K. H., Zhang, L., & Hardy, W. (2003). Is head injury caused by linear or angular acceleration? *Proceedings of the International Research Conference on the Biomechanics of Impacts (IRCOBI)*, (September), 1–12.

King, D. A., & Hume, P. (2010). *INJURIES IN RUGBY LEAGUE: INCIDENCE, INFLUENCES, TACKLES AND RETURN TO PLAY DECISIONS School of Sport and Recreation*.

King, D, Hecimovich, M., Clark, T., & Gissane, C. (2017). Measurement of the head impacts in a sub-elite Australian rules football team with an instrumented patch: An exploratory analysis. *International Journal of Sports Science and Coaching*, *12*(3), 359–370. https://doi.org/10.1177/1747954117710512

King, D, Hume, P., Cummins, C., T, C., Gissane, C., & Hecimovich, M. (2019). Head impact exposure comparison between male and female amateur rugby league participants measured with an instrumented patch. *Journal of Sports Medicine and Therapy*, *4*(1), 024–037. https://doi.org/10.29328/journal.jsmt.1001039

King, Doug, Gissane, C., Brughelli, M., Hume, P. A., & Harawira, J. (2014). Sport-related concussions in New Zealand: A review of 10years of Accident Compensation Corporation moderate to severe claims and costs. *Journal of Science and Medicine in Sport*, *17*(3), 250–255. https://doi.org/10.1016/j.jsams.2013.05.007

King, Doug, Hume, P. A., Brughelli, M., & Gissane, C. (2015). Instrumented mouthguard acceleration analyses for head impacts in amateur rugby union players over a season of matches. *American Journal of Sports Medicine*, *43*(3), 614–624. https://doi.org/10.1177/0363546514560876

King, Doug, Hume, P., Cummins, C., Pearce, A., Clark, T., Foskett, A., & Barnes, M. (2019). Match and Training Injuries in Women's Rugby Union: A Systematic Review of Published Studies. *Sports Medicine*, *49*(10), 1559–1574. https://doi.org/10.1007/s40279-019-01151-4

King, Doug, Hume, P., Gissane, C., & Clark, T. (2016). Similar head impact acceleration measured using instrumented ear patches in a junior rugby union team during matches in comparison with other sports. *Journal of Neurosurgery: Pediatrics*, *18*(1), 65–72. https://doi.org/10.3171/2015.12.PEDS15605

King, Doug, Hume, P., Gissane, C., Kieser, D., & Clark, T. (2018). Head impact exposure from match participation in women's rugby league over one season of domestic competition. *Journal of Science and Medicine in Sport*, *21*(2), 139–146. https://doi.org/10.1016/j.jsams.2017.10.026

Kirkendall, D., Jordan, S., & Garrett, W. (2001). Heading and head injuries in soccer. *Sports Medicine*, *31*(5), 369–386. https://doi.org/10.2165/00007256-200131050-00006

Kirkwood, G., Parekh, N., Ofori-Asenso, R., & Pollock, A. M. (2015). Concussion in youth rugby union and rugby league: A systematic review. *British Journal of Sports Medicine*, *49*(8), 506–510. https://doi.org/10.1136/bjsports-2014-093774

Kleiven, S., Peloso, P., & Von Holst, H. (2003). The epidemiology of head injuries in Sweden from 1987 to 2000. *Inj Control Saf Promot*, *10*(3), 173–180. https://doi.org/10.1076/icsp.10.3.173.14552

Koch, C., & Segev, I. (2000). The role of single neurons in information processing. *Nature Neuroscience*, *3*(11s), 1171–1177. https://doi.org/10.1038/81444

Kuhl, H. N., Ritchie, D., Taveira-Dick, A. C., Hoefling, K. A., & Russo, S. A. (2014). Concussion History and Knowledge Base in Competitive Equestrian Athletes. *Sports Health*, *6*(2), 136–138. https://doi.org/10.1177/1941738113508073

Kumar, S., Narayan, Y., & Amell, T. (2001). Cervical strength of young adults in sagittal, coronal, and intermediate planes. *Clinical Biomechanics*, *16*(5), 380–388.

https://doi.org/10.1016/S0268-0033(01)00023-7

Kumar, Shrawan, Narayan, Y., Amell, T., & Ferrari, R. (2002). Electromyography of superficial cervical muscles with exertion in the sagittal, coronal and oblique planes. *European Spine Journal*, *11*(1), 27–37. https://doi.org/10.1007/s005860100318

Kuo, C., Wu, L., Hammoor, B., Luck, J., Cutcliffe, H., Lynall, R., … Camarillo, D. (2016). Effect of the mandible on mouthguard measurements of head kinematics. *Journal of Biomechanics*, *49*(9), 1845–1853. https://doi.org/10.1016/j.jbiomech.2016.04.017

Kuster, D., Gibson, A., Abboud, R., & Drew, T. (2012). Mechanisms of cervical spine injury in rugby union: A systematic review of the literature. *British Journal of Sports Medicine*, *46*(8), 550–554. https://doi.org/10.1136/bjsports-2011-090360

Langevin, T., Antonoff, D., Renodin, C., Shellene, E., Spahr, L., Marsh, W., & Rosene, J. (2020). Head impact exposures in women's collegiate rugby. *Physician and Sportsmedicine*, *3847*(May). https://doi.org/10.1080/00913847.2020.1770568

Lanzetti, R. M., Lupariello, D., Venditto, T., Rota, P., Guzzini, M., Vadalà, A., … Ferretti, A. (2017). The influence of playing surface on injury risk in italian elite rugby players. *Muscles, Ligaments and Tendons Journal*, *7*(1), 180–185. https://doi.org/10.11138/mltj/2017.7.1.180

Lesinski, M., Prieske, O., & Granacher, U. (2016). Effects and dose-response relationships of resistance training on physical performance in youth athletes: A systematic review and meta-analysis. *British Journal of Sports Medicine*, *50*(13), 781–795. https://doi.org/10.1136/bjsports-2015-095497

Levine, A., & Edwards, C. (1985). The management of traumatic spondylolisthesis of the axis. *The Journal of Bone & Joint Surgery*, *67*(2), 217–226.

Li, X., Lin, C., Liu, C., Ke, S., Wan, Q., Luo, H., … Wu, S. (2017). Comparison of the effectiveness of resistance training in women with chronic computer-related neck pain: a randomized controlled study. *International Archives of Occupational and Environmental Health*, *90*(7), 673–683. https://doi.org/10.1007/s00420-017-1230-2

Limb, M. (2014). Traumatic brain injury carries long term health risks, finds study. *BMJ (Clinical Research Ed.)*, *348*(January), g294. https://doi.org/10.1136/bmj.g294

Linder, A., & Svedberg, W. (2019). Review of average sized male and female occupant models in European regulatory safety assessment tests and European laws: Gaps and bridging suggestions. *Accident Analysis and Prevention*, *127*(February), 156–162. https://doi.org/10.1016/j.aap.2019.02.030

Liss, C., Sanni, A., & McCully, K. (2020). Endurance of the Dorsal and Ventral Muscles in the Neck. *Journal of Functional Morphology and Kinesiology*, *5*(3). https://doi.org/10.3390/JFMK5030047

Liu, Y., Domel, A., Yousefsani, S. A., Kondic, J., Grant, G., Zeineh, M., & Camarillo, D. (2020). Validation and comparison of instrumented mouthguards for measuring head kinematics and assessing brain deformation in football impacts. *ArXiv*.

Ljungquist, T., Harms-Ringdahl, K., Nygren, A., & Jensen, I. (1999). Intra- and inter-rater reliability of an 11-test package for assessing dysfunction due to back or neck pain. *Physiotherapy Research International : The Journal for Researchers and Clinicians in Physical Therapy*, Vol. 4, pp. 214–232. https://doi.org/10.1002/pri.167

Lough, N., & Geurin, A. (2019). Routledge Handbook of the Business of Women's Sport. In *Routledge Handbook of the Business of Women's Sport*. https://doi.org/10.4324/9780203702635

Lumba-Brown, A., Yeates, K. O., Sarmiento, K., Breiding, M. J., Haegerich, T. M., Gioia, G. A., … Timmons, S. D. (2018, November 1). Centers for Disease Control and Prevention Guideline on the Diagnosis and Management of Mild Traumatic Brain Injury among Children. *JAMA Pediatrics*, Vol. 172. https://doi.org/10.1001/jamapediatrics.2018.2853

Maas, A. I., Stocchetti, N., & Bullock, R. (2008). Moderate and severe traumatic brain injury in adults. *The Lancet Neurology*, *7*(8), 728–741. https://doi.org/10.1016/S1474-4422(08)70164-9

Makama, J. G., Garba, E. S., & Ameh, E. A. (2012). Under Representation of Women in Surgery in Nigeria: By Choice or by Design? *Oman Medical Journal*, *27*(1), 66–69. https://doi.org/10.5001/omj.2012.15

Manning, K. Y., Llera, A., Dekaban, G. A., Bartha, R., Barreira, C., Brown, A., … Menon, R. S. (2019). Linked MRI signatures of the brain's acute and persistent response to concussion in female varsity rugby players. *NeuroImage: Clinical*, *21*(November). https://doi.org/10.1016/j.nicl.2018.101627

Mansell, J., Tierney, R., Sitler, M., Swanik, K., & Stearne, D. (2005). Resistance training and head-neck segment dynamic stabilization in male and female collegiate soccer players. *Journal of Athletic Training*, *40*(4), 310–319. Retrieved from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1323293/pdf/i1062-6050-40-4-310.pdf

Marshall, S. W., Guskiewicz, K. M., Shankar, V., McCrea, M., & Cantu, R. C. (2015). Epidemiology of sports-related concussion in seven US high school and collegiate sports. *Injury Epidemiology*, *2*(1). https://doi.org/10.1186/s40621-015-0045-4

Marshall, W. S. W. (1998). The New Zealand Rugby Injury and Performance Project: V. Epidemiology of a season of rugby injury. *British Journal of Sports Medicine*, *32*(4), 319–325. https://doi.org/10.1136/bjsm.32.4.319

Mathias, J. L., & Alvaro, P. K. (2012). Prevalence of sleep disturbances, disorders, and problems following traumatic brain injury: A meta-analysis. *Sleep Medicine*, *13*(7), 898–905. https://doi.org/10.1016/j.sleep.2012.04.006

Mayo Clinic. (2020). Persistent post-concussive symptoms (Post-concussion syndrome). Retrieved October 20, 2020, from Mayo Foundation for Medical Education and Research website: https://www.mayoclinic.org/diseases-conditions/post-concussion-syndrome/symptoms-causes/syc-20353352

Mcbride, L., & Oxford, S. W. (2020). *Cervical Spine Assessment Techniques and Neck Strength Profiles of Elite Rugby Union Players Using an Innovative Measurement Approach*. Retrieved from https://www.medrxiv.org/content/medrxiv/early/2020/06/05/2020.06.04.20121988.full.pdf

McCrea, M., Hammeke, T., Olsen, G., Leo, P., & Guskiewicz, K. (2004). Unreported Concussion in High School Football Players: Implications for Prevention. *Clinical Journal of Sport Medicine*, *14*(1), 13–17. https://doi.org/10.1097/00042752-200401000-00003

McCrory, P. (2001). Do mouthguards prevent concussion? *British Journal of Sports Medicine*, *35*(2), 81–82. https://doi.org/10.1136/bjsm.35.2.81

McCrory, Paul, Feddermann-Demont, N., Dvoøák, J., Cassidy, J. D., McIntosh, A., Vos, P., … Tarnutzer, A. (2017). What is the definition of sports-related concussion: A systematic review. *British Journal of Sports Medicine*, *51*(11), 877–887. https://doi.org/10.1136/bjsports-2016-097393

McCrory, Paul, Meeuwisse, W., Dvořák, J., Aubry, M., Bailes, J., Broglio, S., … Vos, P. E. (2017). Consensus statement on concussion in sport—the 5th international conference on concussion in sport held in Berlin, October 2016. *British Journal of Sports Medicine*, *51*(11), 838–847. https://doi.org/10.1136/bjsports-2017-097699

McCrory, Paul, Meeuwisse, W. H., Aubry, M., Cantu, B., Dvořák, J., Echemendia, R. J., … Turner, M. (2013). Consensus statement on concussion in sport: The 4th International Conference on Concussion in Sport held in Zurich, November 2012. *British Journal of Sports Medicine*, *47*(5), 250–258. https://doi.org/10.1136/bjsports-2013-092313

McCrory, Paul, Meeuwisse, W. H., Aubry, M., Cantu, R. C., Dvorák, J., Echemendia, R. J., … Turner, M. (2013). Consensus Statement on Concussion in Sport-The 4th International Conference on Concussion in Sport Held in Zurich, November 2012. *PM and R*, *5*(4), 255–279. https://doi.org/10.1016/j.pmrj.2013.02.012

McElhaney, J., Snyder, R., States, J., & Gabrielsen, A. (1979). Biomechanical Analysis of Swimming Pool Neck Injuries. *SAE Transactions*, *88*, 494–500.

McGroarty, N. K., Brown, S. M., & Mulcahey, M. K. (2020). Sport-Related Concussion in Female Athletes: A Systematic Review. *Orthopaedic Journal of Sports Medicine*, *8*(7), 1–12. https://doi.org/10.1177/2325967120932306

McKee, A. (2020). CTE resources. Retrieved May 2, 2020, from Concussion Legacy Foundation Reseach Registry website: https://concussionfoundation.org/CTE-resources/research-registry

Mckee, A. C., Cantu, R. C., Nowinski, C. J., Hedley-whyte, T., Gavett, B. E., Budson, A. E., … Stern, R. A. (2010). *Chronic Traumatic Encephalography*. *68*(7), 709–735. https://doi.org/10.1097/NEN.0b013e3181a9d503.Chronic

McKee, A. C., Stein, T. D., Nowinski, C. J., Stern, R. A., Daneshvar, D. H., Alvarez, V. E., … Cantu, R. C. (2013). The spectrum of disease in chronic traumatic encephalopathy. *Brain*, *136*(1), 43–64. https://doi.org/10.1093/brain/aws307

McMillan, T. M., Weir, C. J., & Wainman-Lefley, J. (2014). Mortality and morbidity 15 years after hospital admission with mild head injury: A prospective case-controlled population study. *Journal of Neurology, Neurosurgery and Psychiatry*, *85*(11), 1214–1220. https://doi.org/10.1136/jnnp-2013-307279

McMillan, T., McSkimming, P., Wainman-Lefley, J., Maclean, L., Hay, J., McConnachie, A., & Stewart, W. (2017). Long-Term health outcomes after exposure to repeated concussion in elite level: Rugby union players. *Journal of Neurology, Neurosurgery and Psychiatry*, *88*(6), 505–511. https://doi.org/10.1136/jnnp-2016-314279

Meaney, D. F., Morrison, B., & Bass, C. D. (2014). The mechanics of traumatic brain injury: A review of what we know and what we need to know for reducing its societal burden. *Journal of Biomechanical Engineering*, *136*(2). https://doi.org/10.1115/1.4026364

Meier, M. (2015). The value of female sporting role models. *Sport in Society*, *18*(8), 968–982.

Mez, J., Daneshvar, D. H., Kiernan, P. T., Abdolmohammadi, B., Alvarez, V. E., Huber, B. R., … McKee, A. C. (2017). Clinicopathological evaluation of chronic traumatic encephalopathy in players of American football. *JAMA - Journal of the American Medical Association*, *318*(4), 360–370. https://doi.org/10.1001/jama.2017.8334

Middleton, K., Govus, A., & Clarke, A. (2019). *Nutrition for Sports, Exercise, and Performance: A practical guide for students, sports enthusiasts and professionals* (R. Belski, A. Forsyth, & E. Mantzioris, Eds.). Crows Nest: Allen & Unwin.

Mihalik, J., Bell, D., Marshall, S., & Guskiewicz, K. (2007). Measurements of head impacts in collegiate football players: an investigation of postiional and event-type differences. *Neurosurgery*, *61*(6), 1229–1235.

Mihalik, J., Guskiewicz, K., Marshall, S., Blackburn, J. T., Cantu, R., & Greenwald, R. (2012). Head impact biomechanics in youth hockey: Comparisons across playing position, event types, and impact locations. *Annals of Biomedical Engineering*, *40*(1), 141–149. https://doi.org/10.1007/s10439-011-0405-3

Mohan, M., & Huynh, L. (2019). Sex Differences in the Spine. *Current Physical Medicine and Rehabilitation Reports*, *7*(3), 246–252. https://doi.org/10.1007/s40141-019-00234-7

Mountcastle, V. (1998). *Perceptual Neuroscience: The Cerebral Cortex*. Retrieved from https://books.google.co.uk/books?hl=en&lr=&id=egQPpf-vGh8C&oi=fnd&pg=PR13&dq=cerebral+cortex+of+brain&ots=63JhowZIvj&sig=l4gmnlKTQ3lop8IsqS5gJ0G_rB4&redir_esc=y#v=onepage&q=cerebral cortex of brain&f=false

Murayama, H., Hitosugi, M., Motozawa, Y., Ogino, M., & Koyama, K. (2020). Biomechanical analysis of the head movements of a person thrown by the judo technique 'seoi-nage.' *Neurologia Medico-Chirurgica*, *60*(2), 101–106. https://doi.org/10.2176/nmc.oa.2019-0206

Naish, R., Burnett, A., Burrows, S., Andrews, W., & Appleby, B. (2013). Can a specific neck strengthening program decrease cervical spine injuries in a men's professional Rugby Union team? A retrospective analysis. *Journal of Sports Science and Medicine*, *12*(3), 542–550.

Namjoshi, D. R., Good, C., Cheng, W. H., Panenka, W., Richards, D., Cripton, P. A., & Wellington, C. L. (2013). Towards clinical management of traumatic brain injury: A review of models and mechanisms from a biomechanical perspective. *DMM Disease Models and Mechanisms*, *6*(6), 1325–1338. https://doi.org/10.1242/dmm.011320

Nazarahari, M., Arthur, J., & Rouhani, H. (2020). A Novel Testing Device to Assess the Effect of Neck Strength on Risk of Concussion. *Annals of Biomedical Engineering*, *48*(9), 2310–2322. https://doi.org/10.1007/s10439-020-02504-1

Nemeth, M. C., Park, H., & Mendle, J. (2020). Collegiate female athletes' body image and clothing behaviors. *Fashion and Textiles*, *7*(1). https://doi.org/10.1186/s40691-020-0207-z

Newman, J., Shewchenko, N., & Wlebourne, E. (2000). A proposed new biomechanical head injury assessment function - the maximum power index. *Strapp Car Crash Journal*, *44*, 215–247. Retrieved from https://pubmed.ncbi.nlm.nih.gov/17458729/

Ng, T., Bussone, W., & Duma, S. (2006). The effect of gender and body size on linear accelerations of the head observed during daily activities. *Biomedical Sciences Instrumentation*, *42*, 25–30.

Nightingale, R., Myers, B., & Yoganandan, N. (2015). Neck injury biomechanics. *Accidental Injury: Biomechanics and Prevention*, 259–308. https://doi.org/10.1007/978-1-4939-1732-7_11

Nightingale, R. W., McElhaney, J. H., Camacho, D. L., Kleinberger, M., Winkelstein, B. A., & Myers, B. S. (1997). The dynamic responses of the cervical spine: Buckling, end conditions, and tolerance in compressive impacts. *SAE Technical Papers*. https://doi.org/10.4271/973344

Norton, K. (2019). Standards for Anthropometry Assessment. In *Kinanthropometry and Exercise Physiology*. https://doi.org/10.4324/9781315385662-4

Nusholtz, G., Huelke, D., Lux, P., & Alem, N. (1983). Cervical Spine Injury Mechanisms. *SAE Technical Papers*, *831616*. https://doi.org/https://doi.org/10.4271/831616.

Nyberg, C. C., & Penpraze, V. (2016). Determination of Anthropometric and Physiological Performance Measures in Elite Scottish Female Rugby Union Players. *Int J Res Ex Phys*, *12*(1), 10–16. Retrieved from http://www.western.edu/sites/default/files/page/docs/nyberg.penpraze.fall_.2016.pdf

O'Regan, E. (2019). Huge increase in women diagnosed with concussion "shows risk of playing rugby."

Oliver, P., & Du Toit, D. (2008). Isokinetic neck strength profile of senior elite rugby union players. *Journal of Science and Medicine in Sport*, *11*(2), 96–105. https://doi.org/10.1016/j.jsams.2007.01.009

Ono, Y., Tanaka, Y., Sako, K., Tanaka, M., & Fujimoto, J. (2020). Association between Sports-Related Concussion and Mouthguard Use among College Sports Players: A Case-Control Study Based on Propensity Score Matching. *International Journal of Environmental Research and Public Health*, *17*(12), 4493. Retrieved from https://www.mdpi.com/1660-4601/17/12/4493/htm

Ott, K., Demetropoulos, C. K., Luongo, M. E., Titus, J. M., Merkle, A. C., & Drewry, D. G. (2020). Evaluation of the Whole Body Spine Response to Sub-Injurious Vertical Loading. *Annals of Biomedical Engineering*. https://doi.org/10.1007/s10439-020-02656-0

Owens, T. S., Rose, G., Marley, C. J., Calverley, T. A., Stacey, B. S., Williams, P., … Bailey, D. M. (2019). The changing nature of concussion in rugby union: Looking back to look forward. *Journal of Concussion*, *3*, 205970021986064. https://doi.org/10.1177/2059700219860641

Park, S. E., Choi, D. S., Shin, H. S., Baek, H. J., Choi, H. C., Kim, J. E., … Park, M. J. (2017). Splenial lesions of the corpus callosum: Disease spectrum and MRI findings. *Korean Journal of Radiology*, *18*(4), 710–721. https://doi.org/10.3348/kjr.2017.18.4.710

Patel, V., Patel, A., Harrop, J., & Burger, E. (2014). Spine surgery basics. In *Spine Surgery Basics*. https://doi.org/10.1007/978-3-642-34126-7

Patton, D. A., Huber, C. M., Jain, D., Myers, R. K., McDonald, C. C., Margulies, S. S., … Arbogast, K. B. (2020). Head Impact Sensor Studies In Sports: A Systematic Review Of Exposure Confirmation Methods. *Annals of Biomedical Engineering*, *48*(11), 2497–2507. https://doi.org/10.1007/s10439-020-02642-6

Peolsson, A., ÖBerg, B., & Hedlund, R. (2001). Intra- and inter-tester reliability and reference values for isometric neck strength. *Physiotherapy Research International : The Journal for Researchers and Clinicians in Physical Therapy*, *6*(1), 15–26. https://doi.org/10.1002/pri.210

Pesaresi, M., Soon-Shiong, R., French, L., D.R. Kaplan, Miller, F. D., & Paus, T. (2015). Axon diameter and axonal transport: In vivo and in vitro effects of androgens. *NeuroImage*, *115*, 191–201. https://doi.org/10.1016/j.neuroimage.2015.04.048

Pettersen, J. (2002). Does rugby headgear prevent concussion? Attitudes of Canadian players and coaches. *British Journal of Sports Medicine*, *36*(1), 19–22. https://doi.org/10.1136/bjsm.36.1.19

Pfister, T., Pfister, K., Hagel, B., Ghali, W. A., & Ronksley, P. E. (2016). The incidence of concussion in youth sports: A systematic review and meta-analysis. *British Journal of Sports Medicine*, *50*(5), 292–297. https://doi.org/10.1136/bjsports-2015-094978

Pollock, M., Graves, J., Bamman, M., Leggett, S., Carpenter, D., Carr, C., … Fulton, M. (1993). Frequency and volume of resistance training: effect on cervical extension strength. *Archives of Physical Medicine and Rehabilitation*, *74*(10), 1080–1086. Retrieved from https://www.sciencedirect.com/science/article/abs/pii/000399939390065I

Posthumus, L., Macgregor, C., Winwood, P., Tout, J., Morton, L., Driller, M., & Gill, N. (2020). The physical characteristics of elite female rugby union players. *International Journal of Environmental Research and Public Health*, *17*(18), 1–10. https://doi.org/10.3390/ijerph17186457

Posthumus, M. (2013). The state of women’s rugby union in South Africa: Recommendations for long-term participant development. *South African Journal of Sports Medicine*, *25*(1), 28–35. https://doi.org/10.7196/sajsm.461

PRISP. (2018). England Professional Rugby Injury Surveillance Project 2017-18. In *RFU Season Report*. Retrieved from https://www.englandrugby.com/dxdam/96/960006d9-269d-4250-a15f-d9e62f8bfe70/PRISP_1718.pdf

Quarrie, K. L., & Hopkins, W. G. (2007). Changes in player characteristics and match activities in Bledisloe Cup rugby union from 1972 to 2004. *Journal of Sports Sciences*, *25*(8), 895–903. https://doi.org/10.1080/02640410600944659

Quarrie, K. L., & Hopkins, W. G. (2008). Tackle injuries in professional rugby union. *American Journal of Sports Medicine*, *36*(9), 1705–1716. https://doi.org/10.1177/0363546508316768

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*. https://doi.org/10.1016/j.jsams.2012.08.005

Quarrie, K, Gianotti, S., Chalmers, D., & Hopkins, W. (2005). An evaluation of mouthguard requirements and dental injuries in New Zealand rugby union. *British Journal of Sports Medicine*, *39*(9), 650–654. https://doi.org/10.1136/bjsm.2004.016022

Quarrie, Kenneth, Cantu, R., & Chalmers, D. (2002). Rugby union injuries to the cervical spine and spinal cord. *Sports Med*, *32*(10), 633–653. https://doi.org/10.2165/00007256-200232100-00003

Raftery, M., Tucker, R., & Falvey, É. C. (2020). Getting tough on concussion: how welfare-driven law change may improve player safety—a Rugby Union experience. *British Journal of Sports Medicine*, (June), bjsports-2019-101885. https://doi.org/10.1136/bjsports-2019-101885

Ranson, C., George, J., Rafferty, J., Miles, J., & Moore, I. (2018). Playing surface and UK professional rugby union injury risk. *Journal of Sports Sciences*, *36*(21), 2393–2398. https://doi.org/10.1080/02640414.2018.1458588

Rauen, K., Späni, C., Tartaglia, M. C., Ferretti, M. T., Reichelt, L., Probst, P., … Plesnila, N. (2020). Quality of life after traumatic brain injury: a cross-sectional analysis uncovers age- and sex-related differences over the adult life span. *GeroScience*. https://doi.org/10.1007/s11357-020-00273-2

Rees, P. (2018). RFU’s full-time contracts for England women’s team “hugely significant.” Retrieved from The Guardian website: https://www.theguardian.com/sport/2018/sep/17/rfu-re-introduce-full-time-contracts-england-womens-rugby-union-team

Reider, B. (2012). Sex in sports medicine. *American Journal of Sports Medicine*, *40*(6), 1231–1233. https://doi.org/10.1177/0363546512449812

RFU. (2018). HEADCASE. Retrieved February 17, 2020, from England Rugby website: https://www.englandrugby.com/participation/playing/headcase

Roberts, J. S., Gray, S., & Camacho Minano, M. J. (2019). Exploring the PE context and experience of girls who challenge gender norms in a progressive secondary school. *Curriculum Studies in Health and Physical Education*, 3–17. Retrieved from https://www.tandfonline.com/doi/abs/10.1080/25742981.2019.1696688?scroll=top&needAccess=true&journalCode=rasp21

Roberts, S. P., Trewartha, G., Higgitt, R. J., El-Abd, J., & Stokes, K. A. (2008). The physical demands of elite English rugby union. *Journal of Sports Sciences*, *26*(8), 825–833. https://doi.org/10.1080/02640410801942122

Roberts, S., Trewartha, G., England, M., Goodison, W., & Stokes, K. (2017). Concussions and Head Injuries in English Community Rugby Union Match Play. *American Journal of Sports Medicine*, *45*(2), 480–487. https://doi.org/10.1177/0363546516668296

Roberts, S., Trewartha, G., England, M., Shaddick, G., & Stokes, K. (2013). Epidemiology of time-loss injuries in English community-level rugby union. *BMJ Open*, *3*, 3998. https://doi.org/10.1136/bmjopen-2013

Roof, R., Duvdevani, R., & Stein, D. (1993). Gender influences outcome of brain injury: progesterone plays a protective role. *Brain Research*, *607*(1–2), 333–336. Retrieved from https://www.sciencedirect.com/science/article/abs/pii/000689939391526X

Roos, P. E., Vasavada, A., Zheng, L., & Zhou, X. (2020). Neck musculoskeletal model generation through anthropometric scaling. *PLoS ONE*, *15*(1), 1–21. https://doi.org/10.1371/journal.pone.0219954

Roser, M., Appel, C., & Ritchie, H. (2013). Human Height. Retrieved September 17, 2020, from ourworldindata.org website: https://ourworldindata.org/human-height

Rowson, S., Brolinson, G., Goforth, M., & Duma, S. (2009). Linear and angular head acceleration measurements in collegiate football. *Journal of Biomechanical Engineering*, *131*(6). https://doi.org/10.1115/1.3130454.

Rowson, S., & Duma, S. M. (2013). Brain injury prediction: Assessing the combined probability of concussion using linear and rotational head acceleration. *Annals of Biomedical Engineering*, *41*(5), 873–882. https://doi.org/10.1007/s10439-012-0731-0

Rowson, S., Duma, S. M., Beckwith, J. G., Chu, J. J., Greenwald, R. M., Crisco, J. J., … Maerlender, A. C. (2012). Rotational head kinematics in football impacts: An injury risk function for concussion. *Annals of Biomedical Engineering*, *40*(1), 1–13. https://doi.org/10.1007/s10439-011-0392-4

Rugby, E. (2014). *Women's rugby: Players to be paid as England Sevens turn pro*.

Sakamoto, K., Sasaki, R., Hong, S., Matsukura, K., & Asai, T. (2014). Comparison of kicking speed between female and male soccer players. *Procedia Engineering*, *72*, 50–55. https://doi.org/10.1016/j.proeng.2014.06.011

Salmon, D., Hancock, P., Sullivan, S., Rehrer, N., & Niven, B. (2018). Can Neck Strength be Measured Using a Single Maximal Contraction in a Simulated Contact Position? *Journal of Strength and Conditioning Research*, *32*(8), 2166–2173. Retrieved from https://journals.lww.com/nsca-jscr/Fulltext/2018/08000/Can_Neck_Strength_be_Measured_Using_a_Single.7.aspx?casa_token=eGvpHkAKP5IAAAAA:tnreimVCZNqccaRhaC8VTBLXTLNZsXNR9tWkiRml2fAW-aV_kvUYO_Vrz-MxS9ANqMZ_CULBAaTFsipnLn9U4Yo

Salmon, D., Handcock, P., Sullivan, S. J., Rehrer, N., & Niven, B. (2015). Reliability of repeated isometric neck strength and endurance testing in a simulated contact posture. *Journal of Stre*, *29*(3), 637–646. Retrieved from https://journals.lww.com/nsca-jscr

Salmon, D. M. (2014). *An Examination of Neck Strength, Endurance, Neck Pain and Neck Stiffness in Rugby Union Players*. (August).

Salmon, D., Romanchuk, J., Murphy, I., Sullivan, J., Walters, S., Whatman, C., … Van Der Vis, K. (2020). Infographic. New Zealand Rugby's concussion management pathway. *British Journal of Sports Medicine*, *54*(5), 298–299. https://doi.org/10.1136/bjsports-2019-100950

Sam, C. H. (2019). Shaping Discourse Through Social Media: Using Foucauldian Discourse Analysis to Explore the Narratives That Influence Educational Policy. *American Behavioral Scientist*, *63*(3), 333–350. https://doi.org/10.1177/0002764218820565

Scorza, K. A., Raleigh, M. F., & O'connor, F. G. (2012). Current concepts in concussion: Evaluation and management. *American Family Physician*, *85*(2), 124–132.

Sedeaud, A., Marc, A., Schipman, J., Tafflet, M., Hager, J. P., & Toussaint, J. F. (2012). How they won rugby World Cup through height, mass and collective experience. *British Journal of Sports Medicine*, *46*(8), 580–584. https://doi.org/10.1136/bjsports-2011-090506

Selenke, D. (2020). Rugby. In M. Khodaee, A. Waterbrook, & M. Gammons (Eds.), *Sports-related Fractures, Dislocations and Trauma* (pp. 929–932). https://doi.org/https://doi.org/10.1007/978-3-030-36790-9_67

Seng, K. Y., Peter, V. S. L., & Lam, P. M. (2002). Neck muscle strength across the sagittal and coronal planes: An isometric study. *Clinical Biomechanics*, *17*(7), 545–547. https://doi.org/10.1016/S0268-0033(02)00067-0

Shapiro, S., & Wilk, M. (1965). An Analysis of Variance Test for Normality (complete samples). *Biometrika*, *52*(3/4), 591–611. https://doi.org/10.2307/2333709

Sicard, V., Moore, R. D., & Ellemberg, D. (2018). Long-term cognitive outcomes in male and female athletes following sport-related concussions. *International Journal of Psychophysiology*, *132*(March), 3–8. https://doi.org/10.1016/j.ijpsycho.2018.03.011

Siegmund, G., Winkelstein, B., Ivancic, P., Svensson, M., & Vasavada, A. (2009). The

Anatomy and Biomechanics of Acute and Chronic Whiplash Injury. *Journal of Traffic Injury Prevention*, *10*(2). https://doi.org/https://doi.org/10.1080/15389580802593269

Simon, V. (2005). Wanted: Women in clinical trials. *Science*, *308*(5728), 1517. https://doi.org/10.1126/science.1115616

Sims, S. T., & Heather, A. K. (2018). Myths and Methodologies: Reducing scientific design ambiguity in studies comparing sexes and/or menstrual cycle phases. *Experimental Physiology*, Vol. 103, pp. 1309–1317. https://doi.org/10.1113/EP086797

Singa, J. H., Pitil, P. P., Juliana, W., & Wahed, E. (2020). Player positions: Anthropometric and physical fitness in elite rugby. *International Journal of Physical Education, Sport and Health*, *7*(August), 218–222.

Sinnott, A. M., Kontos, A. P., Collins, M. W., & Ortega, J. (2020). Concussion Symptoms Among Athletes: Preinjury Factors Predict Postinjury Factors. *The Journal of Head Trauma Rehabilitation*, *35*(4), E361–E371. https://doi.org/10.1097/HTR.0000000000000562

Sky sports. (2020). Ireland women receive apology after new jersey launched by models. Retrieved September 17, 2020, from sky sports website: https://www.skysports.com/rugby-union/news/12321/12058274/ireland-women-receive-apology-after-new-jersey-launched-by-models

Spani, C., Braun, D., & Van Eldik, L. (2018). Sex related responses after traumatic brain injury: considerations for preclinical modeling. *Front Neuroendocrinol*, *50*, 52–66. https://doi.org/10.1016/j.yfrne.2018.03.006

Stemper, B., DeRosia, J., Yoganandan, N., Pintar, F., Shender, B., & Paskoff, G. (2009). Gender dependent cervical spine anatomical differences in size-matched volunteers. *Biomedical Sciences Instrumentation*, *45*, 149–154. Retrieved from https://www.researchgate.net/publication/24280814

Stemper, B., Yoganandan, N., & Pintar, F. (2004). Gender and region dependent local facet joint kinematics in rear impact: Implications in whiplash injury. *Spine*, *29*(16), 1764–1771. https://doi.org/10.1097/01.BRS.0000134563.10718.A7

Stewart, W., McNamara, P., Lawlor, B., Hutchinson, S., & Farrell, M. (2016). Chronic traumatic encephalopathy: A potential late and under recognized consequence of rugby union? *Qjm*, *109*(1), 11–15. https://doi.org/10.1093/qjmed/hcv070

Stokes, K. A., Locke, D., Roberts, S., Henderson, L., Tucker, R., Ryan, D., & Kemp, S. (2019). Does reducing the height of the tackle through law change in elite men’s rugby union (The Championship, England) reduce the incidence of concussion? A controlled study in 126 games. *British Journal of Sports Medicine*, 1–6. https://doi.org/10.1136/bjsports-2019-101557

Strimpakos, N., Sakellari, V., Gioftsos, G., & Oldham, J. (2004). Intratester and intertester reliability of neck isometric dynamometry. *Arch Phys Med Rehabil*, *85*(8), 1309–1316. https://doi.org/doi: 10.1016/j.apmr.2003.08.104

Suryanarayana, L., & Kumar, S. (2005). Quantification of isometric cervical strength at different ranges of flexion and extension. *Clinical Biomechanics*, *20*(2), 138–144. https://doi.org/10.1016/j.clinbiomech.2004.10.003

Suzuki, K., Nagai, S., Ogaki, R., Iwai, K., Furukawa, T., Miyakawa, S., & Takemura, M. (2019). Video analysis of tackling situations leading to concussion in collegiate rugby union. *The Journal of Physical Fitness and Sports Medicine*, *8*(2), 79–88. https://doi.org/10.7600/jpfsm.8.79

Swain, M., Pollard, H., & Bonello, R. (2010). Incidence, severity, aetiology and type of neck injury in men’s amateur rugby union: a prospective cohort study. *Chiropractice & Osteopathy*, *18*(18). https://doi.org/10.1186/1746-1340-18-18

Sye, G., Sullivan, S. J., & McCrory, P. (2006). High school rugby players’ understanding of concussion and return to play guidelines. *British Journal of Sports Medicine*, *40*(12), 1003–1004. https://doi.org/10.1136/bjsm.2005.020511

Takemura, M., Schneiders, A. G., Bell, M. L., & Milburn, P. D. (2007). Association of ground hardness with injuries in rugby union. *British Journal of Sports Medicine*, *41*(9), 582–587. https://doi.org/10.1136/bjsm.2007.035568

Tang-Schomer, M. D., Johnson, V. E., Baas, P. W., Stewart, W., & Smith, D. H. (2012). Partial interruption of axonal transport due to microtubule breakage accounts for the formation of periodic varicosities after traumatic axonal injury. *Experimental Neurology*, *233*(1), 364–372. https://doi.org/10.1016/j.expneurol.2011.10.030

Tannenbaum, C., Ellis, R., Eyssel, F., Zou, J., & Schiebinger, L. (2019). Sex and gender analysis improves science and engineering. *Nature*, *575*(7781), 137–146. https://doi.org/10.1038/s41586-019-1657-6

Tanveer, S., Zecavati, N., Delasobera, E., & Oyegbile, T. (2017). Gender Differences in Concussion and Postinjury Cognitive Findings in an Older and Younger Pediatric Population. *Pediatr Neurol*, *70*, 44–49. https://doi.org/0.1016/j.pediatrneurol.2017.02.001

Tator, C. H., Davis, H. S., Dufort, P. A., Tartaglia, M. C., Davis, K. D., Ebraheem, A., & Hiploylee, C. (2016). Postconcussion syndrome: Demographics and predictors in 221 patients. *Journal of Neurosurgery*, *125*(5), 1206–1216. https://doi.org/10.3171/2015.6.JNS15664

Taylor, A. E., Fuller, C. W., & Molloy, M. G. (2011). Injury surveillance during the 2010 IRB Women's Rugby World Cup. *British Journal of Sports Medicine*, *45*(15), 1243–1245. https://doi.org/10.1136/bjsports-2011-090024

Tellez, M. J. A., Silva, A. M., Ruiz, J. R., Martins, S. S., Palmeira, A. L., Branco, T. L., … Sardinha, L. B. (2020). Neck circumference is associated with adipose tissue content in thigh skeletal muscle in overweight and obese premenopausal women. *Scientific Reports*, *10*(1), 1–6. https://doi.org/10.1038/s41598-020-65204-9

Theis, V., & Theiss, C. (2019). Progesterone Effects in the Nervous System. *Anatomical Record*, *302*(8), 1276–1286. https://doi.org/10.1002/ar.24121

Thomas, K. E., Annest, J. L., Gilchrist, J., & Bixby-Hammett, D. M. (2006). Non-fatal horse related injuries treated in emergency departments in the United States. *British Journal of Sports Medicine*, *40*(7), 619–626. https://doi.org/10.1136/bjsm.2006.025858

Thompson, B., Almarjawi, A., Sculley, D., & Janse de Jonge, X. (2020). The Effect of the Menstrual Cycle and Oral Contraceptives on Acute Responses and Chronic Adaptations to Resistance Training: A Systematic Review of the Literature. *Sports Medicine*, *50*(1), 171–185. https://doi.org/10.1007/s40279-019-01219-1

Tierney, G., Lawler, J., Denvir, K., McQuilkin, K., & Simms, C. (2016). risks associated with significant head impact events in elite rugby union. *Brain Injury*, *30*(11), 1350–1361.

Tierney, R., Sitler, M., Swanik, C., Swanik, K., Higgins, M., & Torg, J. (2005). Gender differences in head-neck segmnet dynamic stabilization during head accelaration. *Medicine and Science in Sports and Exercise*, *37*(2), 272–279. https://doi.org/10.1249/01.MSS.0000152734.47516.AA

Tilley, A. (2002). *The measure of man and women: Human factors in design, Revised Edition*. Retrieved from https://books.google.co.uk/books?hl=en&lr=&id=ZuoCDgAAQBAJ&oi=fnd&pg=PA11&ots=PhZabpB8tg&sig=IF8i2jUrGw4fkpeH2zpf92bu2Cc&redir_esc=y#v=onepage&q&f=false

Toffoletti, K., & Palmer, C. (2019). Women and sport in Australia—new times? *Journal of Australian Studies*, *43*(1), 1–6. https://doi.org/10.1080/14443058.2019.1579081

Tucker, R., Raftery, M., Kemp, S., Brown, J., Fuller, G., Hester, B., … Quarrie, K. (2017).

Risk factors for head injury events in professional rugby union: A video analysis of 464 head injury events to inform proposed injury prevention strategies. *British Journal of Sports Medicine*, *51*(15), 1152–1157. https://doi.org/10.1136/bjsports-2017-097895

United Nations. (2007). *Women, gender equality and sport*. Retrieved from https://www.un.org/womenwatch/daw/public/Women and Sport.pdf

Urban, J. E., Davenport, E. M., Golman, A. J., Maldjian, J. A., Whitlow, C. T., Powers, A. K., & Stitzel, J. D. (2013). Head impact exposure in youth football: High school ages 14 to 18 years and cumulative impact analysis. *Annals of Biomedical Engineering*, *41*(12), 2474–2487. https://doi.org/10.1007/s10439-013-0861-z

Vanacore, N., Lehman, E. J., Hein, M. J., Baron, S. L., & Gersic, C. M. (2013). Neurodegenerative causes of death among retired National Football League players. *Neurology*, *80*(13), 1266–1267. https://doi.org/10.1212/01.wnl.0000428873.10254.b7

Vasavada, A., Danaraj, J., & Siegmund, G. (2008). Head and neck anthropometry, vertebral geometry and neck strength in height-matched men and women. *Journal of Biomechanics*, *41*(1), 114–121. https://doi.org/10.1016/j.jbiomech.2007.07.007

Voor, J., Lloyd, A., & Cole, R. (2013). The inlfuence of Compatition on the Efficiency of an isometric muscle contraction. *Journal of Motor Behaviour*, 210–219.

Weiss, E., Siedentopf, C., Hofer, A., Deisenhammer, E., Hoptman, M., Kremser, C., … Delazer, M. (2003). Sex differences in brain activation pattern during a visuospatial cognitive task: A functional magnetic resonance imaging study in healthy volunteers. *Neuroscience Letters*, *344*(3), 169–172. https://doi.org/10.1016/S0304-3940(03)00406-3

Wells, J. C. K. (2007). Sexual dimorphism of body composition. *Best Practice and Research: Clinical Endocrinology and Metabolism*, *21*(3), 415–430. https://doi.org/10.1016/j.beem.2007.04.007

Wilcox, B. J., Beckwith, J. G., Greenwald, R. M., Chu, J. J., Mcallister, T. W., Flashman, L. A., … Wilcox, B. (2014). Head Impact Exposure in Male and Female Collegiate Ice Hockey Players and Simbex have a financial interest in the instruments (HIT System, Sideline Response System. *J Biomech. January*, *3*(471), 109–114. https://doi.org/10.1016/j.jbiomech.2013.10.004

Williams, E., Petrie, F. J., Pennington, T. N., Powell, D. R. L., Arora, H., Mackintosh, K. A., & Greybe, D. G. (2021). Sex differences in neck strength and head impact kinematics in university rugby union players. *European Journal of Sport Science*, (0), 1–17. https://doi.org/10.1080/17461391.2021.1973573

Williams, S., Trewartha, G., Kemp, S., & Stokes, K. (2013, October). A meta-analysis of injuries in senior men’s professional Rugby Union. *Sports Medicine*, Vol. 43, pp. 1043–1055. https://doi.org/10.1007/s40279-013-0078-1

Wilson, J. (2019). Study reveals former football and rugby players six times more likely to have degenerative brain disease, CTE. Retrieved January 22, 2019, from The Telegraph website: https://www.telegraph.co.uk/sport/2019/01/19/study-reveals-former-football-rugby-players-six-times-likely/

Winsper, C., Singh, S. P., Marwaha, S., Amos, T., Lester, H., Everard, L., … Birchwood, M. (2013). Pathways to violent behavior during first-episode psychosis: A report from the UK national EDEN study. *JAMA Psychiatry*, *70*(12), 1287–1293. https://doi.org/10.1001/jamapsychiatry.2013.2445

Winters, J., & DeMont, R. (2014). Role of mouthguards in reducing mild traumatic brain injury/concussion incidence in high school football athletes. *General Dentistry*, *62*(3), 34–38.

Woitowich, N., & Woodruff, T. (2019). Opinion: research community needs to better appreciate the value of sex-based resarch. *Proceedings of the National Academy of Sciences of the United States of America*, *116*(15), 7154–7156. Retrieved from https://doi.org/10.1073/pnas.1903586116

Wolf, J., Stys, P., Lusardi, T., Meaney, D., & Smith, D. (2001). Traumatic axonal injury induces calcium influx modulated by tetrodotoxin-sensitive sodium channels. *Journal of Neuroscience*, *21*(6), 1923–1930. https://doi.org/10.1523/jneurosci.21-06-01923.2001

Women in Sport. (2019). *Literature review: empowering girls through sport*. Retrieved from https://www.womeninsport.org/wp-content/uploads/2019/06/Literature-Review-Gender-Stereotypes.pdf

Wood, R. (2008). Anthropometric Tests. Retrieved April 16, 2020, from Topend Sports Website website: https://www.topendsports.com/testing/anthropometry.htm

Wood, T. A., Morrison, S., & Sosnoff, J. J. (2019). The Role of Neck Musculature in Traumatic Brain Injuries in Older Adults: Implications From Sports Medicine. *Frontiers in Medicine*, *6*, 10. https://doi.org/10.3389/fmed.2019.00053

World Rugby. (2015). Head injury assessment adopted into law. Retrieved June 1, 2020, from World Rugby website: https://www.world.rugby/news/70796?lang=en

World Rugby. (2016). World Rugby Handbook. Retrieved April 1, 2020, from World Rugby website: https://www.world.rugby/handbook/regulations/reg-10?lang=en

World Rugby. (2018a). Record numbers Get Into Rugby in 2017.

World Rugby. (2018b). *World Rugby Year in review 2018* (pp. 50–51). pp. 50–51. Retrieved from http://publications.worldrugby.org/yearinreview2018/en/14-1

World Rugby. (2019). Decision-making framework for high tackles. Retrieved October 21, 2020, from Laws of the Game Rugby Union website: https://laws.worldrugby.org/en/guidelines/13

World Rugby. (2020a). *Accelerating the global development of women in rugby 2017-25*.

World Rugby. (2020b). Age Grade Rugby. Retrieved April 21, 2020, from World Rugby website: https://www.englandrugby.com/participation/coaching/age-grade-rugby

World Rugby. (2020c). Laws of the Game Rugby Union. Retrieved April 21, 2020, from World Rugby website: https://laws.worldrugby.org/?charter=all&language=EN

World Rugby. (2020d). Laws of the Game Rugby Union. Retrieved June 1, 2020, from World Rugby website: https://laws.worldrugby.org/?law=19&language=EN

World Rugby. (2020e). *Summary of transgender biology and performance research*. Retrieved from https://resources.world.rugby/worldrugby/document/2020/10/09/a67e3cc3-7dea-4f1e-b523-2cba1073729d/Transgender-Research_Summary-of-data_ENGLISH-09.10.2020.pdf

World Rugby. (2020f). *Transgender guidline*. Retrieved from https://www.world.rugby/news/591776/world-rugby-approves-updated-transgender-participation-guidelines

World Rugby Handbook. (2019). Regulation 12 : PROVISIONS RELATING TO PLAYERS' DRESS. *World Rugby Handbook*, 191–222. Retrieved from https://www.world.rugby/handbook/regulations/reg-12?lang=en

WRISP. (2018). *Women's Rugby Injury Surveillance Project. Season Report 2017/18* (Vol. 1). Bath.

Wu, L., Nangia, V., Bui, K., Hammoor, B., Kurt, M., Hernandez, F., … Camarillo, D. (2016). In Vivo Evaluation of Wearable Head Impact Sensors. *Annals of Biomedical Engineering*, *44*(4), 1234–1245. https://doi.org/10.1007/s10439-015-1423-3

Yard, E. E., & Comstock, R. D. (2006). Injuries sustained by pediatric ice hockey, lacrosse, and field hockey athletes presenting to United States Emergency Departments, 1990-2003. *Journal of Athletic Training*, *41*(4), 441–449.

Yeomans, C., Comyns, T., Cahalan, R., Warrington, G., Harrison, A., Purtill, H., … Kenny, I. (2020). A comparison of injuries between male and female amateur rugby union players. *British Journal of Sports Medicine*, *54*(1).

Yoganandan, N., Knowles, S., Maiman, D., & Pintar, F. (2003). Anatomic study of the morphology of human cervical facet joint. *Spine*, *28*(20), 2317–2323. https://doi.org/10.1097/01.BRS.0000085356.89103.A5

Yoganandan, N., Kumaresan, S., & Pintar, F. A. (2001). Biomechanics of the cervical spine Part 2. Cervical spine soft tissueresponses and biomechanical modeling. *Current Opinion in Immunology*.

Appendices

Appendix A – Participant Information Sheet

PARTICIPANT INFORMATION SHEET

(Version 1.3, Date: 10/09/2019)

Project Title:

LOOK-A-HEAD to Health and Wellbeing in Rugby Union Swansea University ref: 2016-059

Contact Details:

Dr. Elisabeth Williams
Senior Lecturer, Forensic Biomechanics
A-STEM Research Centre
College of Engineering
Swansea University, Bay Campus
Fabian Way
Swansea
SA1 8EN
[redacted]

Dr. Shane Heffernan
Lecturer, Sport Science
A-STEM Research Centre
College of Engineering
Swansea University, Bay Campus
Fabian Way
Swansea, SA1 8EN
[redacted]

1. Invitation Paragraph

My name is Dr. Elisabeth Williams; I am a senior lecturer the Applied Sport, Technology, Exercise and Medicine (A-STEM) Research Centre in the College of Engineering at Swansea University. A-STEM is conducting a study called LOOK-A-HEAD to assess the effects of repeated head impacts on player health in Rugby Union and you are invited to participate.

2. What is the purpose of the study?

Rugby is the sport of choice for more many people in Wales. As with any contact sport, injuries are a common and expected feature within the game. At the senior and professional level of the game, concussion and serious injuries are particularly topical and regularly relayed in the media. All involved in this study take the safety of players at all levels seriously. A range of initiatives and programmes are in place to minimise serious (harm) injuries, however due to the nature of sport, particularly contact sport; injuries will occur from time to time. Player safety and welfare is paramount – we want to protect the health of athletes over the short and long term. We are not saying there is a problem or a definite link between rugby and long-term health issues. What we are doing is helping Welsh rugby organizations take steps to find out more via this research project. This is not just a matter for rugby but for all of sport.

3. Why have I been chosen?

You have been selected to participate in this research project as you are currently playing rugby union at a professional or elite level. Your participation in this research is voluntary. You are free to withdraw consent and discontinue participation at any time without influencing any present and/or future involvement with Swansea University. Your consent to participate in this research will be indicated by your signing and dating the consent form. Signing the consent form indicates that you have freely given your consent to participate, and that there has been no coercion or inducement to participate by the researchers from Swansea University.

4. What will happen to me if I take part?

You may be asked to complete a pre-competition concussion history questionnaire, a sports concussion assessment baseline evaluation, undertake a measurement of your head and neck and to complete a number reading test. You will also be asked to perform some neck strength tests during preseason, several times during the season and at the end of the season. You will be asked to wear a custom-fit mouthguard which will contain accelerometer and gyroscope sensors during training and matches. To make your own mouthguard, you will be required to have a qualified dentist take impressions of your teeth. These will be used to make the guard for you. During the mouthguard development process, you may be asked by the research and development team for your feedback about how comfortable it is to wear. You may also be asked to specify particular features of your mouthguard which you would like altered to ensure it is comfortable. During preseason, you will be asked to provide a small (6 mL) blood sample and if you are highlighted to have had a head impact during the season, another small blood sample (0.5 or 6mL) will be collected every second day until the end of the return to play protocol.

5. What are the possible disadvantages of taking part?

Only those discomforts and risks that normally occur from participating in rugby union activities. This includes the risk of a sports-related concussion. This risk can be increased if you have had a previous concussion and this will be discussed with you as part of the concussion history assessment. You may be asked to see another health care professional for further assessment and clearance to play as part of this process. You may feel some slight discomfort with wearing the external patches. In the initial stages of mouthguard development, you may find this to be too large. You will not be asked to wear the mouthguard in either training sessions or games until you are completely satisfied it is comfortable for you.

6. What are the possible benefits of taking part?

Information gained from this research has potential to help shape training strategies, and develop prognostic indicators of value to athletes, clinicians, physical conditioners and coaches.

7. Will my taking part in the study be kept confidential?

The data from the research project will be coded and held anonymously in secure storage under the responsibility of the principal investigator of the study in accordance with the requirements of Swansea University. All reference to participants will be by code number only in terms of any research theses and publications. Identification information will be stored on a separate file and computer from that containing the actual data. Only the lead investigators will have access to computerized data. Should a situation occur where you become injured then your identified next-of-kin / legal guardian / parent that has been recorded and/or signed the consent form will be contacted to advise them of the injury, the care provided and where you have been transferred to. The information obtained will also be passed onto the healthcare service as part of the on-going management of your medical care.

8. What if I have any questions?

If you have any questions, please feel free to contact Dr Elisabeth Williams or Dr Shane Heffernan. Any concerns regarding the nature of this project should be notified in the first instance to the Project Supervisor – Dr Williams. Concerns regarding the conduct of the research should be notified to Dr Williams or Dr Heffernan. Please take the necessary time you need to consider the invitation to participate in this research. It is reiterated that your participation in this research is completely voluntary. If you require further information about the research topic, please feel free to contact Elisabeth Williams (details are at the top of this information sheet). You may withdraw from the study at any time without any adverse consequences of any kind. You may ask for a copy of your results at any time and you have the option of requesting a report of the research outcomes at the completion of the study.

Appendix B – Participant Consent Form

PARTICIPANT CONSENT FORM

(Version 1.3, Date: 10/09/2019)

Project Title:
LOOK-A-HEAD to Health and Wellbeing in Sports

Contact Details:

Dr. Elisabeth Williams Senior Lecturer, Forensic Biomechanics A-STEM Research Centre College of Engineering Swansea University, Bay Campus Fabian Way Swansea, SA1 8EN [redacted]	Dr. Shane Heffernan Lecturer Sport Science A-STEM Research Centre College of Engineering Swansea University, Bay Campus Fabian Way Swansea, SA1 8EN [redacted]

	Please initial
1. I confirm that I have read and understood the information sheet dated 26/03/2018 (version number 1.2) for the above study and have had the opportunity to ask questions.	
2. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason, without my medical care or legal rights being affected.	
3. I understand that sections of any of data obtained may be looked at by responsible individuals from the Swansea University or from regulatory authorities where it is relevant to my taking part in research. I give permission for these individuals to have access to these records.	
4. I agree to take part in the above study, to have a photographic image to be taken for educational and research purposes only and that in taking my photo the face image will be made opaque.	

Name of Participant	Date	Signature
Name of Person Taking Consent	Date	Signature
Researcher	Date	Signature

Appendix C – Medical History Questionnaire

PARTICIPANT QUESTIONNAIRE

All answers will be kept strictly confidential outside of the immediate project team

Institution/Team	
Name	
DOB	
Weight (kg)	
Height (cm)	
Playing Position	
Years Competing	
Level (highest)	
Do you normally wear a mouthguard?	
Have you previously suffered concussion?	
If yes, how many and when (year)?	
Did you get injured last season?	
If yes, please list the injuries you have sustained playing rugby	1 2 3
How long were you away from sport?	1 2 3
When did it happen (year)?	1 2 3
How did it happen?	1 2 3
Are you willing to partake in a future epigenetic study?	