Swansea University
Prifysgol Abertawe

Analysis of Head Acceleration Kinematics in Collegiate and Elite Women's Rugby Union

Freja Jo Petrie

Submitted to Swansea University in fulfilment of the requirements for the Degree of Master of Sports Science, Swansea University

2020

Abstract

Women are 1.4 times more likely to suffer concussion in collegiate sports than men. Despite this, the concussion protocols used in women's rugby union are derived almost exclusively from androcentric data. However, androcentric data has limited generalisability to women due to sexual dimorphisms within axonal structure, cervical anatomy and stabilising cervical musculature. These anatomical and functional differences may result in female head acceleration kinematics differing from those reported in androcentric data. Therefore, the study aim was to identify female-specific head acceleration kinematics in elite and collegiate women's rugby union.

In the collegiate players, instrumented mouthguards (Protecht™, SWA Ltd, Swansea, UK) were used alongside video footage to quantify head acceleration during matches. These mouthguards employed tight sensor-skull coupling and had been validated. For elite players, video footage of two international matches were analysed. Video from both cohorts were analysed using identical criteria for comparison of head acceleration kinematics across cohorts.

The instrumented mouthguard system recorded 73 verified and low-pass filtered head acceleration events (HAEs) in collegiate players, with median peak linear and rotational accelerations of 11.9 g (interquartile range (IQR 7.3) and 4291.7 rad/s^2 (IQR 646.9), respectively. Collegiate players experienced twice the number of HAEs per playing minute compared to elite players. Whiplash-style kinematics not previously documented in androcentric data were observed in both cohorts. As players fell, muscular control of the neck was often lost, resulting in a whiplash motion of the head hitting the ground. These kinematics were evident in 31.5% of collegiate and 4.2% of elite contact events, and likely resulted from poor neck strength and fall technique. Indeed, as world ranking of elite teams increased, incidence of whiplash-style kinematics decreased.

Overall, these findings highlight distinct sexual dimorphisms in head acceleration kinematics. It is therefore necessary to understand female-specific head kinematics for the development of mitigation strategies.

Declaration 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.

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.

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] (candidate)

Date **20/09/2020**

Table of Contents

Acknowledgements

I would first like to thank my supervisor, Dr Elisabeth Williams for the hours of help and support I have received over the course of this masters. Her enthusiastic approach and constant support have made this year so enjoyable and I have gained so much from her supervision. In addition, I would like to thank my co-supervisor, Dr Kelly Mackintosh, and Dr Melitta McNarry for their continued support and advice on the social aspects of the project. Additionally, I would like to thank Dr Desney Greybe for the development of the filtering application used in this study and for all the encouragement and technical advice I have received throughout the year.

I would like to extend my gratitude to Keytree Ltd for their generous sponsorship of this masters and technical support with the mouthguard software, both at short notice and outside of normal office hours.

I would like to extend my gratitude to those involved with Knowledge Economy Skills Scholarship 2 (KESS 2 West Wales) for the sponsorship of this project and for the provision of extensive upskilling opportunities.

Furthermore, I would like to thank Victoria Hayden for her continued support collecting match data in all weathers and all research participants from the women’s rugby team for their cooperation with all testing and in persevering with our mouthguard system.

List of Figures

List of Tables

Abbreviations

ATD	Anthropometric test device
ANOVA	Analysis of variance
CTE	Chronic Traumatic Encephalopathy
DOMS	Delayed Onset Muscle Soreness
HAE	Head acceleration event
HIA	Head Injury Assessment
iMG	Instrumented mouthguard system
IQR	Interquartile range
PLA	Peak linear acceleration
PPE	Personal protective equipment
PRA	Peak rotational acceleration
SCAT5	Sports Concussion Assessment Tool 5
SD	Standard deviation
SIS	Second Impact Syndrome
SRC	Sports related concussion
STA	Soft tissue artefact
WSHK	Whiplash style head kinematics
WR	World Rugby
WN	World Ranking

Chapter 1: Introduction

Women's rugby union has seen unprecedented growth following its recent professionalisation in 2018 (World Rugby, 2019b). Asides from the physiological benefits associated with regular exercise, involvement in sport greatly improves resilience (Ho, Louie, Chow, Wong, & Ip, 2015), quality of life and the ability to cope with stress (Eime, Young, Harvey, Charity, & Payne, 2013). The physicality of the game empowers women and encourages focus on performance rather than societal ideals of appearance (Fields & Comstock, 2016). Involvement within the sport should therefore be considered of great benefit to the mental, physical and social health of women.

Despite these benefits, the high concussion incidence within rugby, and other contact sports, may threaten the long-term brain health of players (Bitchell, Mathema, & Moore, 2020a; Cunningham, Broglio, O'Grady, & Wilson, 2020). Concussion can be caused either by a direct blow to the head or from an impact to the torso that transmits force through the neck to the head (McCrory et al., 2017). These direct or indirect impacts cause rapid acceleration of the brain inside the skull (McCrory et al., 2017). Consequently, the brain is injured through contusion, strain and traumatic alterations to cellular neurometabolism (Moore, Jaffee, Ling, & Radovitzky, 2020). Symptoms range from ataxia to amnesia and may take months to resolve (Preiss-Farzanegan, Chapman, Wong, Wu, & Bazarian, 2009).

At the community level, 75% of male players self-reported at least one concussion over their playing careers (Hume et al., 2016). Even a single concussion elevates the risk of dementia by 17%, with four concussions elevating this risk to 180% (Fann et al., 2018). Whilst these figures have sparked significant research effort to increase our understanding in male rugby players, there is a noticeable lack of research considering the occurrence and impact of concussion in females (Costello, Bieuzen, & Bleakley, 2014; Preiss-Farzanegan et al., 2009). Indeed, there is currently no validated head impact telemetry data for women's rugby at any level. This is especially concerning given that non-scalable anatomical differences within female brains increase their vulnerability to accelerative injury (Dollé et al., 2018; Stemper et al., 2008) and may explain the elevated risk of sport-related concussion (SRC) documented across a range of sports (Zuckerman et al., 2015). Additionally, women suffer a greater symptom burden than men, even when impact magnitudes are equal (Henry, Elbin, Collins, Marchetti, & Kontos, 2016).

Head acceleration kinematics may differ across playing levels. Less experienced players in collegiate teams may have less proficient contact technique (Kerr et al., 2018) or be less conditioned to withstand repetitive collisions. Whilst elite players likely have more proficient contact technique and are better conditioned, injury kinematics may be altered as the physicality of the game and power of the athletes increases.

1.1 Aim

The aim of this study was to examine head impact kinematics observed within women's collegiate and elite rugby union.

The achievement of this aim was facilitated through the analysis of female-specific head acceleration kinematics via video data of collegiate and elite match play. The use of instrumented mouthguards (iMG) to quantify collegiate head acceleration event (HAE) magnitudes gave further context to head acceleration kinematics present within women's rugby. Anthropometric data from a sample of each player demographic was gathered to further inform the results. It was hypothesised that head acceleration kinematics would differ between the elite and collegiate demographic, and that the kinematic data gathered from female rugby players would differ from published androcentric literature.

Chapter 2: Literature Review

Rugby Union (rugby) is a full contact, team sport characterised by frequent tackles, rucks and mauls interspersed with fast running breaks. Despite women's rugby being professionalised thirty-three years later than the men's game, the number of female participants is rising quickly with 2.7 million players registered worldwide (World Rugby, 2019b). Whilst many players enjoy the physical nature of rugby, contact events are responsible for the majority of concussions reported in the sport (Fuller, Brooks, Cancea, Hall, & Kemp, 2007).

2.1 Incidence

In recent years the rate of reported concussions within men and women's rugby has increased. This rise can be attributed to the growing popularity of the sport (Zhang, Sing, Rugg, Feeley, & Senter, 2016), improved concussion awareness (Hickling et al., 2020) and the development of injury reporting protocols (Fuller, Kemp, & Raftery, 2017). However, although concussion reporting is improving in the men's game, the women's game remains under-researched. Indeed, a meta-analysis of concussion in rugby union included 37 studies, but found two studies that reported the incidence in the women's game (Gardner, Iverson, Williams, Baker, & Stanwell, 2014). This meta-analysis found that concussion incidence was reported at 0.55 per 1000 playing hours in the women's game, eight times lower than reported in men of the same level (Gardner, et al, 2014b). However, other studies report that the female brain has an increased vulnerability to accelerative forces (Antona-Makoshi, Mikami, Lindkvist, Davidsson, & Schick, 2018; Dollé et al., 2018; Preiss-Farzanegan et al., 2009). Therefore, it is likely that the gender disparity in concussion incidence reflects inadequate injury reporting in the female game, rather than a lower incidence rate per se. Concussions can only be diagnosed by qualified doctors, who are rarely present at women's matches, particularly at the lower levels of the sport. Consequently, the only recognised and recorded concussions are those experienced by individuals who seek health care. Two more recent studies in elite female rugby players report a concussion incidence of 6.2 and 15 per 1000 playing hours (Kemp et al., 2018; King, Hume, Gissane, Kieser, & Clark, 2018). To date, no study has reported concussion incidence in collegiate or community women's rugby.

Reports of concussion incidence in men's rugby vary between studies, but generally range from 13.3 to 21.5 per 1000 playing hours (Kemp, Brown, Stokes, & Roberts, 2018; Kemp & Smith, 2019; Rafferty et al., 2019). Concussion risk across playing level is not consistently reported: certain studies state incidence increases as playing level increases (Hunter et al., 2019; Roberts, Kemp, Morgan, & Stokes, 2020; Kemp & Smith, 2019), whereas others report no significant difference (Barden et al., 2018; Bitchell, Mathema, & Moore, 2020b). Additionally, whether the relative risk of concussion differs between tacklers and ball carriers is not clear. Specifically, in professional rugby league, ball carriers had a higher concussion risk than tacklers (Gardner et al., 2015; King, Hume, Milburn, & Guttenbeil, 2010) but the opposite is reported in rugby union, despite the similar tackle styles across both sports (Cross et al., 2019; Stokes et al., 2019). These differences may result from differing relative contact exposure across studies, therefore future research may benefit from reporting the ratio of non-injurious to injurious contact.

Although not reported through academic channels, several professional players have spoken publicly about their concussion experiences. An article from a popular rugby union forum listed professional players who had retired due to rugby-related Traumatic Brain Injuries (TBI), based on data extracted from news articles (Table 1), (Blitz defence, 2018). The proportion of female players listed is small but can be explained by the recent professionalisation of the sport. A single concussion elevates the likelihood of dementia diagnosis by 18%, while four concussions reportedly elevate that likelihood to 183% (Fann et al., 2018).

Table 1: Professional players retired following repeated concussions

Player	Reported Concussion load	Sex
Elton Flatley	7 in 2 years	Male
Shontayne Hape	'More than 20'	Male
Micheal Lipman	'Possibly 30' over 12 years	Male
Justin Blanchet	4 over 12 months	Male
Bernard Jackman	20 over 3 seasons, '35-40' throughout career	Male
Craig Clarke	10 over 22 months	Male
Jonathan Thomas	Diagnosed with epilepsy thought to have been brought on by multiple head traumas	Male
Kat Merchant	11 over a 9-year international career	Female
Marie-Alice Yahe	'At least five'	Female

2.2 The Gender Gap in Data

World Rugby (WR) has made efforts to reduce the concussion incidence within the sport through education, trialled law changes and injury management protocols. The data used to formulate these recommendations, however, was based predominantly on the male demographic, thus creating a gender gap in the data. A gender gap relates to the absence of female cohorts studied within the research that dictates health policy, medical treatment and safety standards (Criado Perez, 2019). Consequently, women are left at risk of avoidable harm and are less likely to have positive outcomes following illness or injury (Buvinic & Levine, 2016; Holman, Stuart-Fox, & Hauser, 2018). Biological differences such as body size, hormonal profiles and structural anatomy limit the extent to which male-derived data can be generalized to women. Within rugby, sex differences in playing experience and access to coaching (Sport Wales, 2013) widen the gap between male and female play beyond biological differences.

In sports and exercise medicine research, women represent only 39% of study populations (Costello et al., 2014). The relative exclusion of women likely results from the belief that hormonal variability across the menstrual cycle confounds results, meaning more participants are required to power a study (Bruinvels et al., 2017). Where women are included in participant populations, data is rarely sex disaggregated. In a review of 100 randomised control trials in health research, only four studies separated data by sex (Welch et al., 2017). As women comprise only a small proportion of study populations, failure to sex-disaggregate data prevents the reporting of female-specific findings (Criado Perez, 2019). Additionally, the hybridisation of male and female data may lead to erroneous conclusions as sex-specific anatomical and hormonal differences are not accounted for. This failure to address sex differences is common across research and industry, severely disadvantaging female health and quality of life (Criado Perez, 2019).

England rugby published an injury surveillance project in 2018 to monitor injury risk in community matches (Rugby Football Union, 2014). However, neither this report nor the youth version of this report considered the female demographic (Hancock & Barden et al., 2018). Injury surveillance specific to women was only conducted in the elite game, despite clear statements from the union that the published results are not suitable for generalisation to other demographics (Kemp, Fairweather, Williams, Stokes, West, Phillips, Byrne, et al., 2018).

2.3 Brain Injury Nomenclature

The 2016 consensus definition for sport-related concussion (SRC) is as follows:

'Sport-related concussion is a traumatic brain injury induced by biomechanical forces. SRC may be caused either by a direct blow to the head, face, neck or elsewhere on the body with an impulsive force transmitted to the head. SRC typically results in the rapid onset of short-lived impairment of neurological function that resolves spontaneously. However, in some cases, signs and symptoms evolve over a number of minutes to hours. The clinical signs and symptoms cannot be explained by drug, alcohol, or medication use, other injuries or other comorbidities' (McCrory et al., 2017).

Brain injury can be caused by many different mechanisms within varied contexts. Although many definitions are used interchangeably, Table 2: Brain injury nomenclature provides definitions of general terminology. To remain consistent with current literature, all reporting of other studies will use the same terminology as published.

Table 2: Brain injury nomenclature

Name or acronym	Definition
Head injury	A general term that encompasses all injuries to the face and head including skull fracture, traumatic brain injury and breakage of facial bones
Brain injury	A general term to describe any trauma within the brain
TBI	A sudden, inflicted injury to the brain. Injury can result from direct impacts to the head that cause acceleration of the brain within the skull or indirect impacts to the body that transmit accelerative force through the neck to the brain (Savitsky, Givon, Rozenfeld, Radomislensky, & Peleg, 2016) This term encompasses all severities
mTBI	Mild traumatic brain injury – a Glasgow coma scale score of 13-15, can occur with or without loss of consciousness, (Khan & Faisal, 2018).
Concussion	Concussion is considered a subset of mTBI. It is the term most familiar to the general public and most used in publicly available information
SRC	A sports-related concussion, which occurs during sports training or matches, induced by biomechanical forces'; 'concussion that occurs within a sporting context as opposed to accidental injury such as falls or vehicle collisions', (McCrory et al., 2017).
HAE	Head acceleration event. In this study, an HAE refers to an observation of contact with the head, or a sharp whiplash motion of the head.
Direct mechanism	Concussion is caused by direct contact with the head, for example a collision between the head and shoulder of another player.
Indirect mechanism	Concussion is caused in the absence of direct contact with the head. This occurs when an impact to the body transmits accelerative forces through the neck into the skull.
Post-Concussion Syndrome	Continued concussion symptom burden beyond the typical recovery time of two weeks, (Turner & LaBella, 2020).

2.4 Concussion Symptomology

Symptoms of concussion can present immediately, or hours after the injury (Hobbs, Young, & Bailes, 2016). Current brain imaging protocols cannot yet capture the acute structural alterations often present post-concussion, therefore symptomology acts as a marker for functional deficits within the brain (Johnston, Ptito, Chankowsky, & Chen, 2001). Symptoms of concussion include amnesia, loss of consciousness, behavioural or emotional changes, cognitive impairment, seizure, balance deficits and neck pain (McCrory et al., 2017). These symptoms are generally transient but may alter in severity or presentation throughout recovery (McCrory et al., 2017). In those who are concussed, 15% develop Post-Concussion Syndrome (PCS), (Kemp & Smith.,2019; Roberts et al., 2020), defined as continued symptom burden beyond the typical recovery time of two weeks (Turner & LaBella, 2020). Since this condition is thought to result from the non-recovery of damaged axons, the greater anatomical vulsnerability of the female brain is associated with greater incidence of PCS in women (Dollé et al., 2018; Turner & LaBella, 2020).

In concussed men, self-reported symptom severity significantly correlates to length of recovery and may be a valid predictor of expected recovery time (Gallagher et al., 2018b). Conversely, this correlation was not demonstrated in female cohorts, with women generally taking 69% longer to return to play than men (Gallagher et al., 2018a). Dollé et al (2018) suggest that the greater vulnerability of the female brain may explain this extended recovery.

2.5 Neurophysical Mechanisms of Brain Injury

Concussive injuries result from rapid acceleration of the head that damages the microstructure of the brain (McCrory et al., 2017). Although linear and rotational acceleration seldom occur independently of each other, the predominate acceleration type can influence the neuropathological changes typically seen in TBI (Kleiven, 2013). Linear acceleration causes predominantly focal injuries and skull fractures, whereas rotational acceleration produces both focal and diffuse injuries (Kleiven, 2013). Under rotational acceleration, the effects of inertial, centrifugal and Coriolis forces accumulate to cause shear strains within brain tissue (Stemper et al., 2015).

These accelerative forces induce both primary and secondary injury phases within the brain (Dixit, Ross, Goldman, & Holzbaur, 2008; Salehi, Zhang, & Obenaus, 2017). The primary injury phase begins on point of impact and occurs as a direct consequence of accelerative forces exceeding tissue tolerance (Salehi et al., 2017). Disruption to the blood-brain barrier, contusion and haematoma can occur as a result of this mechanical damage (Kurland, Hong, Aarabi, Gerzanich, & Simard, 2012). A further primary outcome is traumatic axonal injury; common across all severities of TBI (Sollmann et al., 2018; Walker & Tesco, 2013). This damage to microtubules within axons causes disruption to sodium and calcium neurometabolism (Moore et al., 2020). Secondary injury occurs indirectly as a result of the trauma and downstream pathophysical processes following dysfunctional cell signalling, the release of proteases and altered cerebral blood flow (Churchill, Hutchison, Graham, & Schweizer, 2020; Sorby-Adams, Marcoionni, Dempsey, Woenig, & Turner, 2017; Winkler, Minter, Yue, & Manley, 2016). Secondary axonal swelling, raised intercranial pressure (Beyer & Johnson, 2020) and inflammation further contribute to overall concussion severity (Margulies & Thibault, 1992; Smith & Meaney, 2000).

2.6 Kinematic Mechanisms of Injury

Generally, there is a greater propensity for SRC during matches than training (McGuine et al., 2019). The most common mechanisms of SRC are suggested to be player-to-player contact (66%), contact with a ball or stick (18%) or contact with the ground (18%) (McGuine et al., 2019). In rugby, there is a higher reported incidence of player-to-player or player-to-ground contact causing injury than contact with the ball (Cross et al., 2019). In high school rugby, 72.4% of injuries were reported to occur in the tackle, 10% in the ruck and 7% in a scrum (Solis-Mencia, Ramos-Álvarez, Murias-Lozano, Aramberri, & Saló, 2019). Of these injuries, 17% were concussions. In male tacklers, head-to-head contact had the greatest propensity to cause concussion followed by head-to-elbow or head-to-knee (Tucker, Hester, Cross, Kemp, & Raftery, 2017a). This is partially consistent with other literature (Sullivan et al., 2009), where head-to-head, head-to-ground and head-to-knee impacts had significantly greater propensity to cause a concussion than other head impact mechanisms. Impacts with high concussion propensity were found to occur less frequently than head-to-trunk, lower limb and pelvis impacts that have comparatively low concussion propensity (Cross et al., 2019).

Tackle Technique and Concussion

The tackle is defined by WR as the ball carrier being ‘held by one more opponents and being brought to the ground’ (World Rugby, 2019a). The majority of concussions are reported to occur within tackles and, in androcentric studies, tacklers are more likely to be concussed than carriers (Kemp, Brown, et al., 2018; Kemp & Smith, 2019).

Tackle Height

Tackle height is often targeted in concussion mitigation interventions. In 2019, a reduced tackle height ruling was trialled in the Rugby Football Union Championship Cup (Stokes et al., 2019). The intended result of this intervention was to reduce head-to-head contact between players in the tackle. Fifty-four control matches with standard tackle height were analysed followed by thirty-six intervention matches where the tackle height was reduced to the line of the armpit. Concussion incidence rose as the legal tackle height was lowered, rising from 16.9 concussions per 1000 player hours in standard ruling to 27.3 per 1000 playing hours in intervention ruling. Whilst the authors concluded that this intervention encouraged desired behaviours in play (such as bending at the waist), concussion incidence significantly increased, therefore original ruling was reinstated. No other trials have been completed in the female or community demographics.

Arm Positioning

Rugby tackles can be made with several different arm positionings. These include the active shoulder tackle, where the tackler uses their shoulder as the first point of contact, and the smother tackle, where the tackler prevents an offload by wrapping up the ball with their arms (World Rugby, 2020a). Concussion propensity is elevated when tacklers fail to maintain the arm wrap around the ball carrier (Suzuki et al., 2020a). In the men’s game, active shoulder tackles have a higher propensity to cause a HAE than smother tackles (Tucker, Hester, et al., 2017a), but no research of this type has been completed in a female cohort.

Head Positioning

WR state that the correct positioning of the tackler’s head during contact is ‘behind or to the side of the carrier and never in front’ (World Rugby, 2020a). Incorrect head positioning significantly elevates concussion incidence to 69.4 per 1000 tackles compared to 2.7 per 1000 in tackles where correct positioning is used (Sobue et al., 2018; Tierney, Lawler, Denvir, McQuilkin, & Simms, 2016). In collegiate men’s rugby, 8%

of tackles were performed with incorrect head positioning (Sobue et al., 2018). Reported reasons for incorrect head positioning were to protect an upper body injury, force of habit or it being unavoidable in certain cases (Sobue et al., 2018). In addition to falling in front of the ball carrier, tackling with the head positioned looking downwards significantly elevates concussion risk in the tackler by 4.6 times (Suzuki et al., 2020a). Suzuki et al (2020a) suggest that this increased risk occurs as the tackler is less aware of players around them and cannot appropriately respond to avoid injury.

Tackle Speed and Direction

Rugby players are generally taught to use fast line speed to gain possession of the ball. Tackler acceleration can prevent the carrier from gaining momentum and carrier acceleration increases the likelihood of breaking through a tackle (Gabbett & Kelly, 2007a). However, as line speed increases tackling proficiency decreases, particularly the ability to maintain recommended body positioning and arm wrap (Gabbett & Kelly, 2007b). As this decreased proficiency is combined with greater force transfer at speed, concussion propensity significantly increases (Tucker, Hester, Cross, Kemp, & Raftery, 2017b). Comparatively, if players in tackling or ball carrying roles shorten their steps before contact (reducing speed and indicating preparedness for the tackle) injury propensity decreases (Burger et al., 2015). Limiting acceleration into tackles is key to reduce the concussion risk of both tacklers and ball carriers (Cross et al., 2019; Tucker, Hester, et al., 2017b) yet is difficult to enforce. Law changes such as the shortening of offside distances (preventing excessive acceleration) may be, therefore, required.

Tackles from the side or behind the ball carrier were the most common cause of overall injury in men’s rugby (Quarrie & Hopkins, 2008), but front-on tackles were most associated with concussion (Tucker, et al., 2017a). The reasoning behind this is not fully understood, however, Tucker, et al., (2017b) suggest that front-on collisions may result in greater force transfer during the tackle. Front-on tackles may also be indicative of tackles where the ball carrier has not performed evasive footwork (known to decrease concussion risk) (Suzuki et al., 2020a). Additionally, contact to the front of a player may also force a backwards fall, where the ball carrier cannot anticipate their landing or protect themselves from incoming ruckers.

2.7 Multiple Concussions and Impact Density

There is an increasing body of evidence that exposure to multiple mild traumatic brain injuries (mTBIs) may elevate the risk of long term neurodegenerative disease (Fann et al., 2018; Guskiewicz et al., 2003). A significant proportion of contact sport athletes will be exposed to repeated head acceleration events over their playing careers (Hume et al., 2016). Elite level male rugby players self-reported 3.5 ± 2 concussions over their careers and male community level players reported 2.9 ± 2 concussions, whereas people who had never played a contact sport reported 0.4 ± 1 concussions (Hume et al., 2016). These concussed participants had significantly worse executive functioning and cognitive flexibility than the non-concussed group (Hume et al., 2016). The concussion exposure experienced by rugby players may predispose this demographic to neurodegenerative disease (Bailes, Petraglia, Omalu, Nauman, & Talavage, 2013). A single concussion reportedly elevates the likelihood of dementia diagnosis by 18%, and likelihood may be elevated by 183% following four concussions (Fann et al., 2018). Although few rugby players have been diagnosed with Chronic Traumatic Encephalopathy (CTE), many players report experiencing multiple concussions over their careers (Stewart, McNamara, Lawlor, Hutchinson, & Farrell, 2016). In a cohort of twenty-five retired rugby league players, the average concussion exposure was 8.5 (Hume et al., 2017, Pearce, Rist, Fraser, Cohen, & Maller, 2018). Despite these players being retired for over ten years, significantly reduced visuomotor reaction times and poorer cognitive performance were recorded in comparison to controls who had never played a contact sport (Hume et al., 2017). The self-reported, retrospective design used in both studies may limit data accuracy, however, it is unlikely this concussion incidence is overreported as only obvious or severe symptomology would have been recalled. The increased exposure to concussive events means that rugby players, as a demographic, are at higher risk of dementia, Parkinson’s disease and CTE (Alosco et al., 2018; Esopenko, Simonds, & Anderson, 2018).

In addition to the number of HAEs, time between events (density) may be a key predictor of concussion severity (Karton, Hoshizaki, & Gilchrist, 2020). When HAEs are grouped closer together, injury severity in animal models increased (Prins, Alexander, Giza, & Hovda, 2013). In humans, increased HAE density may prolong recovery times and symptom burden (Vagnozzi et al., 2010). When HAE magnitude and frequency experienced by concussed and non-concussed players were compared, no significant differences were observed, however, players that were concussed demonstrated significantly greater acceleration over time (Broglio, Lapointe, O'Connor, & McCrea, 2017). Broglio et al., (2017) acknowledge that more research is needed to confirm this hypothesis, but it is likely that frequent head impacts reduce the maximum recoverable volume of the brain, extending the symptom burden.

2.8 Subconcussive Impacts

Head acceleration events that lack the symptom presentation required for concussion diagnosis are termed subconcussive (Nauman, Talavage, & Auerbach, 2020). Subtle functional differences have been detected within vestibular and corticomotor systems after repeated subconcussive impacts, in the absence of any other symptomology (Black et al., 2020; Ewers, 2020). Therefore, low magnitude head impacts may contribute to long term neurodegeneration, even if they appear symptomless (Bailes et al., 2013).

Vestibular Deficits Following Repeated Subconcussive Accelerations

Research has shown that the function of the vestibular system, namely balance and spatial orientation (Precht, 2012), can be compromised following just ten football headers (Hwang, Ma, Kawata, Tierney, & Jeka, 2017). Linear acceleration of the head during headers was measured via instrumented patches and averaged 14.5 g. After participants completed these headers vestibular processing deficits were immediately detectable. In addition to these processing deficits, the subconcussive cohort did not display the expected musculoskeletal learning effects following repetition of a balance task. The hindrance of musculoskeletal learning may elevate injury risk following impaired proprioception and coordination. Whilst Hwang et al., (2017) report that all deficits returned to baseline within twenty-four hours, there is potential that recovery may be undermined by prolonged or ongoing exposure to subconcussive impacts.

The vestibular system is also heavily involved in executive function and visual attention (Master et al., 2018). These deficits are associated with prolonged concussion recovery in children and can explain symptoms such as behaviour change and visuomotor disturbance. Compromised visuomotor processing speed post subconcussive impact (Beattie & Magee, 2008), limits the ability of players to react quickly to impending contact or make snap-decisions to avoid injury (Honda, Chang, & Kim, 2018). In the context of rugby, this may include controlling the landing from a fall or protecting the head during contact.

Cortico-Motor Disturbances

Subconcussive impacts can also adversely affect corticomotor functions. In boxers, nine minutes of sparring increased corticomotor inhibition by 6% in comparison to non-contact matched controls (Cournoyer & Hoshizaki, 2019). Although inhibition recovered to baseline levels within twenty-four hours, if experienced in play, this impairment would likely remain present throughout a match. This reduced neuromuscular control subsequently elevates the risk of musculoskeletal and concussive injury (Herman et al., 2017). The sparring group also demonstrated worse cognitive function scores, with deficits evident beyond twenty-four hours post the sparring bout. Although impact severity was not quantified, the importance of recovery time between subconcussive exposure is highlighted. As people are exposed to repetitive subconcussive accelerations, neuronal tissue experiences low-level damage. As subconcussive load builds over years of play, this microdamage accumulates, contributing to the onset of dementia, CTE and Parkinson’s disease (McKee et al., 2013).

2.9 Neurodegenerative Disease

Microstructural neuronal damage from repeated head accelerations may accumulate over a playing career and elevate the risk of neurodegenerative disease (Fann et al., 2018). Of particular concern is CTE; a neurodegenerative disease first discovered in boxers and retired American football players (Solomon, 2018). Symptoms develop decades after retirement and include progressive cognitive decline, motor impairment and behavioural changes (Golden & Zusman, 2019).

Few retired rugby players have been diagnosed with CTE despite concussion incidence being similar across rugby and American football (King, Hume, Brughelli, & Gissane, 2015; Prien, Grafe, Rössler, Junge, & Verhagen, 2018). The earlier professionalisation of American football may account for the different CTE epidemiology, as more American football players have reached the age of disease presentation. At present, CTE has not been diagnosed in women (Bieniek et al., 2020), despite evidence that the female brain is more vulnerable to accelerative trauma (Dollé et al., 2018; Preiss-Farzanegan et al., 2009). Since women’s rugby was professionalised 33 years after the male game, it may be decades before women develop CTE. As such, sporting and research communities have a unique opportunity to intervene and prevent an epidemic of concussion-related neurodegeneration.

2.10 Concussion Diagnosis

SRCs have not yet been detected via medical imaging and often have transient symptomology (Gunasekaran, Hodge, Pearce, King, & Fraser, 2020). This makes diagnosis difficult, especially where players are highly motivated to continue playing.

Concussion can only be diagnosed by trained medics. At elite levels, medical professionals are present at all matches and strict concussion management protocols are adhered to. The Head Impact Assessment (HIA) protocol was devised by WR in 2015 to aid identification, diagnosis and management of potential concussions (Fuller et al., 2020). If a medic identifies a potentially concussive event, the three-part protocol begins with an off-field assessment and a SCAT5 (Sports Concussion Assessment Tool 5) test.

Despite WR using evidence-based practices, there are still significant problems with current protocols. The SCAT5 score from the HIA is compared to baseline tests to acknowledge individual proficiency across test variables. There are anecdotal reports of athletes deliberately underperforming in baseline tests to improve the likelihood that they pass assessments during play (Beattie & Magee, 2008).

In community rugby, absence of pitch-side medical personnel render the HIA unsuitable, therefore WR recommend a ‘recognise and remove’ program instead (Gardner, Iverson, Huw Williams, Baker, & Stanwell, 2014). The protocol states that ‘Any player showing signs of a potential concussion should be removed from play and seek medical advice’ (World Rugby, 2019d). Coaches, officials, parents and players subsequently become responsible for identifying potential concussions. The efficacy of this approach is highly dependent on the ability of the public to identify suspected concussions, accurately perceive risk and speak up to suggest removal from play.

When surveyed, parents had more concussion knowledge than players: 83% of parents could recognise a concussion (Sye, Sullivan, & McCrory, 2006), yet half of teenage rugby players were not aware of concussion guidelines and almost 80% did not seek medical clearance before returning to play (Sullivan et al., 2009). In age-grade rugby, parents encourage healthcare-seeking behaviour and adherence to medical advice (Kay, Register-Mihalik, Ford, Williams, & Valovich McLeod, 2017). In collegiate players, the tough attitude famous in rugby may minimise the perceived severity of the injury. This behaviour originates from a desire to support the team, game day sacrifice (prioritising game success over injury prevention) and the general expectation of this attitude from the team (Madrigal, Robbins, Gill, & Wurst, 2015). Whilst rugby can greatly improve resilience (Morgan, 2016), the drive to continue to play whilst injured is detrimental to player welfare. As this attitude is often coupled with limited concussion awareness (Sye et al., 2006), players may struggle to voluntarily remove themselves from play.

To mediate this, WR have made concussion education compulsory for match officials. Although concussion reporting has improved (Hickling et al., 2020), officials at amateur levels cannot be expected to identify all suspected concussions due to the high player-to-official ratio. This is particularly true in matches as play commonly continues around injured players and spectator attention follows the movement of the ball. Elite rugby benefits from real-time video observation that allows even momentary symptomology to be quickly identified and reviewed. Delayed identification of injury may allow recovered symptoms to go unnoticed, leaving the player at elevated risk of subsequent injury (Vagnozzi et al., 2010).

2.11 Return to Play After a Concussive Injury

WR require that all players diagnosed with a concussion must complete the graduated return to play protocol (World Rugby, 2019c). This seven-stage protocol is strictly enforced in the elite player, yet at community level adherence is limited. In concussed community players, 78% did not receive concussion advice, 87% returned to play within one week and compliance with return to play advice was 9% (Hollis, Stevenson, McIntosh, Shores, & Finch, 2012). Players who did not adhere to the return to play program were significantly less likely to recover fully, even when age and sex differences were accounted for (Hiploylee et al., 2017).

Even if return to play protocols are adhered to, subtle neurological deficits remain after the player appears asymptomatic (Buckley, Oldham, & Caccese, 2016). Risk of concussion triples in players with three previous concussions compared to non-concussed players (Guskiewicz et al., 2003). For six to eight months post SRC, women had significant cognitive processing deficits such as slower reaction times, slower automatic response inhibition and reduced cognitive flexibility (Guskiewicz et al., 2003). These prolonged deficits limit the ability of the athlete to anticipate and react to contact events, elevating the risk of subsequent concussive and musculoskeletal injury (Ellemberg, Leclerc, Couture, & Daigle, 2007). Furthermore, a history of concussion is associated with higher head acceleration and reduced preparatory cervical muscle activity during the tackle (Bussey et al., 2019). Despite the lower accelerative tolerance of the female brain (Ellemberg et al., 2007; Gallagher et al., 2018a), return to play guidelines are not sex-specific.

2.12 Why are Women More Susceptible to Concussion?

Women are 1.4 times more likely to experience an SCR, yet this is not reflected in injury surveillance reports (Covassin, Stearne, & Elbin, 2008; Kemp, Fairweather, Williams, Stokes, West & Phillips, 2018; Kemp & Smith, 2019). The elevated concussion risk in women is likely a consequence of sex differences to neuroanatomy (Dollé et al., 2018) cervical anatomy (Stemper et al., 2008b), self-report bias (Meehan, Mannix, Oêbrien, & Collins, 2013) and physical literacy (Zwolski, Quatman-Yates, & Paterno, 2017).

Sex Differences in Neuroanatomy

Ultrastructural analysis of human axons in-vitro revealed that the cross-sectional-area of the female axon was 20% smaller than that of a male and had 55% fewer microtubules (Dollé et al., 2018). Mathematical modelling of axonal stretch injury found higher microtubule strain in axons of a smaller diameter (containing fewer microtubules), compared to axons with a larger diameter (and greater number of microtubules) when exposed to the same level of dynamic stretch (Dollé et al., 2018). Therefore, microtubules with a smaller diameter (as in female brains) fail at a lower applied stretch.

Additionally, female axons developed greater undulations than those in males in response to equal injury exposure (Dollé et al., 2018). Dollé et al., (2018) reported that axons with greater undulation had higher calcium concentrations than axons with less severe undulations. This calcium influx acts to disrupt cell signalling and activate proteases causing further chemical damage to the axonal structure (Yuen, Browne, Iwata, & Smith, 2009). Twenty-four hours post injury, female axons had a greater loss of axon function (defined as being able to propagate calcium signals) (Dollé et al., 2018). These findings demonstrate that differing axonal structure predisposes females to more severe axon pathology than males following comparable accelerative loading.

Sex Differences in Cervical Anatomy

The strength of cervical musculature is a ‘significant modifiable risk factor’ in concussion prevention (Cole, 2018). In high school athletes, for every 0.45 kg increase in neck strength, the risk of suffering a SRC was reduced by 5% (Collins et al., 2014). Greater neck strength may attenuate acceleration of the head, reducing the transmission of forces to the brain (Caccese et al., 2017). The neck strength of females is consistently weaker than that of males (Eckner, Oh, Joshi, Richardson, & Ashton-Miller, 2014; Gutierrez, Conte, & Lightbourne, 2014). In addition to weaker cervical musculature, the structure of the female cervical spine reduces the force generating capacity of the surrounding musculature (Streifer et al., 2019). Females have decreased spinal stiffness (Stemper et al., 2008), a greater range of extension-flexion motion (Lind, Sihlbom, Nordwall, & Malchau, 1989), and smaller segmental supports between vertebrae (indicating less stable intervertebral coupling) (Stemper et al., 2008). These non-scalable sex differences in cervical anatomy mean greater relative strength may be needed for females to benefit from the same force attenuation.

Neck Strength Training

As accelerative forces are transmitted to the head via the neck, greater neck strength acts to stabilise the head post contact and reduce inertial loading of the head (Collins et al., 2014; Eckner, O’Connor, Broglio, & Ashton-Miller, 2018). The relationship between neck strength and concussion is a relatively new concept, therefore specific training is not commonly undertaken by rugby players. Training exercises commonly include maximal voluntary contractions of the head against a wall-mounted gym ball or isometric holds off the floor (Axen, Haas, Schicchi, & Merrick, 1992). Completion of these exercises five times a week, for four to seven weeks improved flexion strength by 156%, extension by 162% and lateral flexion by 173% in a non-athletic female population (Axen et al., 1992). Whilst this training intensity may be too great (due to delayed onset muscle soreness (DOMS) affecting game performance), when reasonably scaled such techniques may be of benefit to players. Neck strength was a predictor of concussion in basketball, soccer and lacrosse players, with every 0.45 kg increase in neck strength decreasing concussion odds by 5% (Collins et al., 2014). Although not yet trialled in rugby, Collins et al., (2014) conclude that targeted neck strengthening programs may be a primary prevention mechanism for concussion. This is of particular importance to women as weaker cervical anatomy means women may require greater relative neck strength than men to benefit from equal force attenuation (Yoganandan, Bass, Voo, & Pintar, 2017).

Female Self-Report Bias Myth

Older research may attribute the greater symptom reporting from concussed women to self-report bias. It has been reported that women tend to verbalise their symptoms more than men, particularly regarding mental health (Mackenzie, Gekoski, & Knox, 2006; Thompson et al., 2016; Tjepkema., 2008). In high school athletes, females were more likely than males to report a concussion (Meehan et al., 2013), even after both sexes were provided with an educational intervention (Miyashita, Diakogeorgiou, & VanderVegt, 2016). Whilst women are more likely to engage in health-care seeking behaviours (Lichtman et al., 2018), women with chronic pain frequently reported being ‘mistrusted’ and ‘psychologised’ by healthcare providers and that their pain experiences were not taken seriously (Fillingim, King, Ribeiro-Dasilva, Rahim-Williams, & Riley, 2009). In women’s rugby, similar bias may be observed as people wrongly believe the sport is ‘softer’ than the male game therefore injuries obtained are less serious. In addition, female rugby players may be less likely to report concussion symptoms than male players. As there are substantially fewer female rugby players than male, women’s teams may be less likely to have similarly trained replacements (World Rugby, 2017). As such women may feel a duty to continue play whilst injured.

Physical Literacy and Exposure to Contact Sports

A person can be described as physically literate if they have the ‘motivation, confidence, physical competence, knowledge and understanding to value and take responsibility for engagement in physical activities for life (Zwolski et al., 2017). Poor physical literacy can elevate injury risk and reduces the likelihood of lifetime engagement in physical activity (Zwolski et al., 2017). Participation in sports heavily influences the development of physical literacy, yet half as many school-age girls are sufficiently active in comparison to boys (Tyler et al., 2016). Whilst the gap is beginning to close (National Assembly for Wales & Health, 2019), gender differences in activity levels whilst current collegiate-level players were in school may affect their physical health later in life.

Current collegiate players would have attended primary school between 2004 and 2009. During this time girls were offered a wider range of sports than boys but were less likely to take part in contact sports and were less physically active (Sports Council for Wales, 2007). Early childhood is a critical period for the development of physical literacy (Barnett et al., 2016; Barnett, van Beurden, Morgan, Brooks, & Beard, 2009) and structured activities are more effective at building competence than natural play alone (Altunsöz & Goodway, 2016; Barnett et al., 2016). As boys join the sport early, they can be gradually conditioned to conduct specific movement patterns, whereas girls may miss out on these opportunities for motor development. In 2007, rugby was listed as a curricular activity for 86% of boys and 82% of girls in Welsh primary schools (Sports Council for Wales, 2007). The provision of rugby at primary schools may be made easier as sexes can be mixed and contact load is less than that at secondary schools. Despite being listed, only 7% of Welsh schools had girl's rugby teams compared to 33% that had boy's teams (Sports Council for Wales, 2007). Rugby is very ingrained in Welsh culture, therefore the gender differences reported may be far wider in other countries.

At the time when current collegiate-level players were at secondary school, girls were still less likely than boys to be a member of a sports club or have the appropriate skills and confidence to take part (Sport Wales, 2016). In the 2013 school sport survey the gender gap remained, with boys more likely to regularly participate in a sport (Sport Wales, 2013). During adolescence, involvement in physical activity declines, especially in girls (Martins et al., 2019). This decline is thought to result from loss of interest, a dislike of playing 'masculine' sports and concern over body image (Slater & Tiggemann, 2010). A greater number of girls (30%) self-reported that 'they were not good at sports' compared to only 18% of boys (Sport Wales, 2013). At secondary school, participation in women's rugby reduced further and no contact sport made the top ten girl's extracurricular activity (Sport Wales, 2013). In comparison, rugby was the second most common boy's sport, played by 35% of survey participants (Sport Wales, 2013).

2.13 Research Techniques for Measuring Inertial Loading of the Head

Cadaver and Anatomic Test Devices and Computer Modelling

Several attempts have been made to accurately measure inertial loading of the head, through video mapping, cadaveric studies or head impact telemetry systems. To avoid ethical limitations in experimental studies, cadavers can be used to model the human anatomy and its response to external stimuli. However, deceased tissue behaves differently to live tissue: haemorrhage will be absent upon impact and post-mortem changes alter tissue strength and structure (Kent et al., 2003). Intercranial pressure sensors can be used to partially overcome this, however, the extent of primary and secondary injury is difficult to ascertain (Hardy et al., 2007). Individual differences in cadavers or live participants may also confound results, so computational modelling may minimise confounding variables (Ghajari, Hellyer, & Sharp, 2017). Levels of expected strain or brain pressures can be estimated and correlated with injury. The use of anthropometric testing devices (ATDs) alongside finite element modelling is sufficiently sensitive to model multiple areas in the brain, including grey and white matter (Post, Rousseau, Kendall, Walsh, & Hoshizaki, 2015). A key limitation of ATDs is the limited generalisation to female participants. Current female ATDs are scaled down versions of 50th percentile man (representing the smaller metrics of the female spine), yet the differences between male and female anatomy both in spinal segments and the surrounding soft tissue go beyond those associated with geometric scaling (Yoganandan et al., 2017).

Video Analysis in Injury Identification

Video analysis is currently used at the elite levels of rugby to identify potentially injurious events. Interstudy comparisons are largely precluded however due to a lack of consistency across video coding protocols. An international consensus statement regarding best-practice for rugby injury identification was produced to improve methodological consistency between studies (Hendricks et al., 2020). Of the 17 referenced research articles in this statement, none included or referred to female players. Consequently, female specific kinematics are not included in these international rugby recommendations, which are thus not applicable to one quarter of the global rugby playing population. Future video analysis protocols can be improved as research projects are undertaken in injury kinematics in women’s rugby.

Motion Analysis Systems

Optical motion tracking systems can gather kinematic data by tracking reflective markers attached to biological landmarks. These systems are often designed for gait analysis study and settings are adapted to quantify head acceleration with varying levels of success (Merriaux, Dupuis, Boutteau, Vasseur, & Savatier, 2017). Many systems are not portable, facilitating only laboratory study (Peters, Galna, Sangeux, Morris, & Baker, 2010; Van der Kruk & Reijne, 2018). In the case of rugby, ecological validity is lost as participants cannot ethically reproduce the tackle intensity and power present in game play. Participants also fall from the tackle onto a mat, rather than the ground, therefore falling techniques utilised would not be representative of match play. Further validity is lost due to the trade-off between sampling frequency and video resolution (Van der Kruk & Reijne, 2018). The rugby tackle is a highly dynamic motion, yet optoelectric systems are at their most accurate and precise when recording more static movements. Data quality is therefore reduced as given picture resolution decreases as sampling rate increases (Merriaux et al., 2017). Additionally, data may be lost as cameras can only detect markers in line of sight. As the tackle involves players in close proximity, markers may be obscured requiring players to repeat more tackles before enough useable data is generated.

Development and Validation of Head Impact Telemetry Systems

Research study participants cannot ethically replicate match contact intensity outside of the playing or training environments. Measurement of live team sports, therefore, offers a unique opportunity to measure real-time human head injury data. In rugby matches, players expose themselves to a wide range of impacts without experimenter intervention. The subsequent investigation of kinematic variables surrounding head impacts can identify potential risk factors. These impacts can be quantified using head impact telemetry systems (HITs). These systems record linear acceleration using accelerometers and rotational velocity via gyroscopes (O’Connor, Rowson, Duma, & Broglio, 2017). Rotational velocity is then differentiated into rotational acceleration. These data are transmitted wirelessly to a receiver, where impact waveforms are displayed (Greybe, Jones, Brown, & Williams, 2020).

In recent years, the development of HITs have progressed to non-helmeted sports with evolving inertial measurement unit technology incorporated into mouthguards. Despite the technological development in this area (Bartsch, Samorezov, Benzel, Miele, & Brett, 2014), many studies have used sensors in helmets or adhered to the skin where considerable confounding soft tissue artefact (STA) issues limit the data accuracy and reliability. For example, sensors embedded in American football helmets have recorded impacts up to 98 g (Schnebel, Gwin, Anderson, & Gatlin, 2007), yet when compared to a Hybrid III Headform ATD, 55% of helmet-recorded impacts had absolute error greater than 15% (Jadischke, Viano, Dau, King, & McCarthy, 2013). It is pertinent to note that such testing has limited validity as the plastic surface of the head form cannot replicate the soft tissue artefact seen in humans (Nevins, Smith, & Kensrud, 2015). Only two studies have attempted to quantify head acceleration in women’s rugby. One study in women’s rugby league used instrumented patches on the mastoid process and the other used instrumented headbands (King et al., 2018; Langevin et al., 2020). In both cases, sensor-skull coupling was poor, resulting in high levels of soft tissue artefact. Inaccurate measures of acceleration limit the validity of subsequent analysis, inter-study comparison, computational models and the efficacy of subsequent healthcare interventions.

Chapter 3: Methodology

This study analysed the head impact kinematics of collegiate and elite female rugby union players. Ethical approval for this work was granted by the Swansea University College of Engineering Research Ethics Committee (ref: 2016-059).

At the start of the 2019 UK university rugby season, 13 players from a UK university women's first XV rugby team were fitted with bespoke instrumented mouthguards (iMGs) (Protecht^{TM}, SWA Ltd, Swansea, Wales, UK). The iMGs were used to quantify the head linear and rotational acceleration of HAEs over five full and two half matches. All HAEs included in the analysis were video verified.

This team competed in the British University College Sport (BUCS) Premier South league. BUCS matches in this league are filmed by an analyst, usually from the home team and generally taken from the halfway line. This footage was provided to the researcher by the team for home games. For away games, analyst footage was sent by the opposition following the match. For all games, supplementary video footage was recorded by the researcher and assistants from different locations around the pitch, including roving cameras following play along the sideline.

In addition to video verification of iMG data, this video footage was used to analyse the kinematic variables associated with each observed HAE for all players on the pitch. Due to some poor video quality issues and video equipment failure, this analysis was performed on three full and two half matches.

For the video analysis of HAE kinematics in elite women's rugby, footage from two elite, international women's matches were analysed following their broadcast on publicly available platforms. Access to unedited television footage from a match between the 2020 first and second world-ranked teams was provided by New Zealand Rugby (Wellington, New Zealand). Television footage of the 2020 Six Nations match between the 2020 fourth and ninth world-ranked teams was obtained from Rugby All Nations, (2020).

For both collegiate and elite matches, HAEs were identified via video observation. HAEs were not linked to concussion diagnoses due to the absence of medical professionals at matches in the collegiate cohort. Medical information was not available for elite players.

3.1 Research Participants

The Collegiate Cohort

In the collegiate cohort, player demographic, anthropometric and head impact telemetry data were collected from one team. At the start of the season, all players from this team attended a research information seminar, which explained data collection processes and the ethical, health and safety procedures in place for the duration of the study. All members of this team then completed a consent form and participant questionnaire. The questionnaire included age, playing experience and injury history, including concussions. The collegiate teams played in the BUCS premier women's division over the 2019-2020 season and were part of a university high-performance program. The typical training load of this team was two hours of strength training, two and a half hours of game simulation, an one hour team run and one match per week. Match summaries reported by BUCS were gathered for all matches from the women's playing league and the equivalent men's league over the 2019-2020 playing season to allow comparison of winning margins between the men and women's rugby (Appendix A).

Collegiate Cohort Anthropometrics

At the start of the season, anthropometric measurements were taken from one collegiate team. Participant height was measured using a stadiometer to the nearest millimetre (Seca Portable Stadiometer 225). The participant stood straight with heels tight to the back of the stadiometer and took a deep breath in as the measurement was taken. Height was measured three times to then averaged. Body mass was measured in kilograms using electronic scales to one decimal place (Seca Digital Scales 770).

Elite Player Anthropometrics

Height and weight data for all elite players were publicly available, published on each national rugby federation's website (New Zealand Rugby, 2020; Ultimate Rugby, 2020b, 2020a; Welsh Rugby Union, 2020).

Elite Matches

One match was taken from the 2019 Women’s Rugby Super Series tournament played between the world-ranked number one (WN1) and two (WN2) teams. New Zealand Rugby kindly provided extra footage of this match for analysis. The second match was taken from the 2020 Six Nations tournament played between world-ranked four (WN4) and nine (WN9) teams. The world ranking for each team was as reported by WR in May 2020 (World Rugby, 2020b). Additionally, match summaries reported by the Six Nations tournament were gathered for all women’s and men’s matches from the 2019 and 2020 competition to allow comparison of winning margins between the men and women’s competition.

Anthropometric data for the elite cohort was sourced through publicly available squad statistics. Whilst the accuracy of these measurements cannot be guaranteed, 26 WN1, 23 WN2, 20 WN4 and 24 WN9 team players had anthropometric data reported on their respective national rugby federation websites.

3.2 Analysis of Observed Head Acceleration Events

Video Analysis

BUCS matches in this league are filmed by an analyst from the home team stood on the halfway line. This footage was provided to the researcher by the collegiate team for home games. For away games, analyst footage was sent by the opposition following the match. Extra angles were filmed by the researcher and assistants positioned at either end of the pitch to enable clearer observations where appropriate. This footage was timestamped to allow time matching of acceleration events. Position and play times were noted for all collegiate players that had anthropometric measurements taken. For the elite cohort, games were filmed professionally from multiple angles.

Coding of Video Events

Analysis of collegiate and elite video was completed by one researcher blinded to quantified head acceleration data. The video analysis protocol was identical between cohorts and generally consistent with the consensus framework for video analysis of rugby union (Hendricks et al., 2020). This framework was based on predominantly male study populations, therefore variables relating to the falling phase of contact were added based on observations of female players in the current study.

Kinematics of Head Acceleration Events

The cause of each HAE was attributed to one or more of the three descriptor categories in Table 3. An ethogram methodology was adapted from animal behaviour studies to quantify observed behaviour from video footage. In animal studies, the ethogram is a method of quantifying behaviour via a dictionary of possible actions without inferring the cause or subsequent actions (Crews, Braude, Stephenson, & Clardy, 2020). When translated into sports science research, the ethogram becomes a standardised classification system that allows comparability across studies and objective decision making.

Table 3: Ethogram for head acceleration events

Measure	Definition
Cause of Acceleration	
Indirect	A collision or impact to the body that transmits accelerative forces through the neck into the head. The head is not directly contacted.
Player-to-player contact	A collision or impact to the head as contact is made with a hard or soft body part of another player.
Head-to-ground contact	A collision or impact to the head as contact is made between the player's head and the ground.
Other	A collision or HAE by any other mechanism not listed.
Phase	
1. Initial contact	The HAE is experienced while the player is standing and their bodyweight is supported by their legs.
2. During the fall from contact	The HAE occurs between the time the player is no longer supporting their bodyweight until one second after the landing. The player has landed from the fall if at least one knee is in contact with the ground.
3. Post fall from contact	Any HAE experienced beyond one second post landing.
Player-to-Player Contact	
Soft body part	Chest, torso, upper leg, upper arm.
Hard body parts	Head, shoulder, elbow, forearm, upper and lower back, hip, knee, shin, boot

3.3 Head Acceleration Events Quantified via Instrumented Mouthguards

Instrumented Mouthguard System

A bespoke instrumented mouthguard (iMG) (Protecht^{TM}, Sports Wellbeing Analytics Ltd, Swansea, Wales, UK) was used in this study to measure the inertial loading of the skull. Tri-axial accelerometers and a tri-axial gyroscope were embedded within the guard (aside the fifth molar). Accelerometers recorded linear acceleration in g (1 g = 9.81 ms^{-2}), at 1000 Hz (sampled at 952 Hz, consistent with the gyroscope). The gyroscope measured rotational velocity in radians per second (rad s^{-1}) at 952 Hz. All electrical components within the iMGs were encased in a biocompatible coating (Parylene C, SCS Coatings Ltd, Woking, UK) and were not harmful if swallowed. During development, the iMG system underwent systematic validation testing (Greybe et al., 2020).

To limit the recording of movement not associated with head impacts, the trigger threshold for the iMG recording was set at 10 g as Ng, Bussone, & Duma, (2006a) found that linear acceleration of the head during naturally occurring movements (such as running) did not exceed 9.5 g. A single threshold was applied as linear acceleration values have been reported not to be affected by gender and body mass (Ng, Bussone, & Duma, 2006b). As forces associated with running or jumping are naturally occurring, it is likely that the microstructure of the brain has adaptive tolerance to these accelerations. The 10 g threshold used in this study is consistent with roughly 40% of other studies (King, Hume, Gissane, Brughelli, & Clark, 2016), whilst the other studies use higher thresholds of between 14 and 30 g. Movement artefact from poor sensor-skull coupling can elevate impact magnitudes (Wu et al. 2016) and result in false positive recordings. With tighter coupling, as in bespoke iMGs, using a threshold above 14 g could cause up to 42% of potential impacts to be missed (King et al., 2015). During iMG development, the trigger threshold was set at 8 g to account for the increased vulnerability of the female brain (Dollé et al., 2018). However, this threshold was too low to prevent noise artefacts overwhelming legitimate data, so the original value of 10 g was retained for this study(Ng et al., 2006b). Once triggered, the iMG recorded 104 ms of raw linear acceleration and rotational velocity data. This was transmitted, in real-time, as an impact event to a side-line receiver unit, where it was stored for offline processing and analysis.

Mouthguard Fitting and Player Familiarisation

At the start of the season, five forwards and eight backs had dental impressions taken by a dentist to make the bespoke iMGs. Tight coupling is vital for head impact telemetry systems to limit the effects of soft tissue artefact (STA) (Wu et al., 2016). Therefore, the fit of each player’s iMG was checked at the start of the season to ensure tight coupling to the teeth in addition to player comfort. Ill-fitting iMGs were re-moulded by dipping the edges in hot, but not boiling water, then fitting them to the player’s teeth. If this did not achieve a satisfactory fit, iMGs were returned to the manufacturer and replaced.

The iMGs were worn at all contact training sessions to allow for player familiarisation and throughout all BUCS matches. After each use, iMGs and iMG cases were disinfected thoroughly with manufacturer-recommended cleaning tablets.

Match Day Protocols for Mouthguard System

Players were given their iMGs 20 minutes before the start of each match to allow for pre-match familiarisation. The receiver was positioned on the halfway line at the shoulder height of the players. This allowed for better signal quality, especially where players received impacts facing away from the receiver. IMGs were worn for the duration of the match and notes were made of minutes and position played.

Post Processing of Mouthguard Data - Impact Verification

To ensure good quality data, only HAEs that passed strict verification criteria were included in the final analysis. Earlier studies have reported high impact magnitudes (Schnebel et al., 2007) impact frequencies (King, Hume, Brughelli, & Gissane, 2015a) and overall incidence per game (King et al., 2019). However, these studies may substantially overestimate legitimate values as STA exaggerates impact magnitudes. Additionally, false positives from shout, bite, insertion and removal artefacts may be included in analyses and further elevate HAE incidence. Whilst this earlier research aided the development of sensor technology, inaccuracy threatens the efficacy of injury prevention protocols derived from these data. A legitimate acceleration waveform should have a relatively smooth, bell-shaped curve (Bartsch et al., 2014) as the head accelerates and decelerates during the HAE (Figure 1). Shout, bite and removal/insertion artefacts were identifiable as distinct spiked waveforms (Figure 2), with peaks indicating sharper acceleration profiles than would be realistic for a human head (Bartsch et al., 2014).

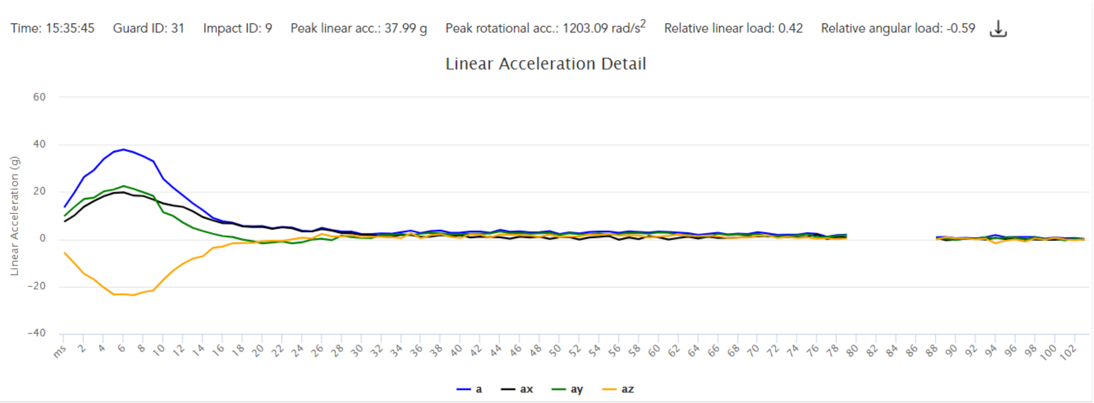
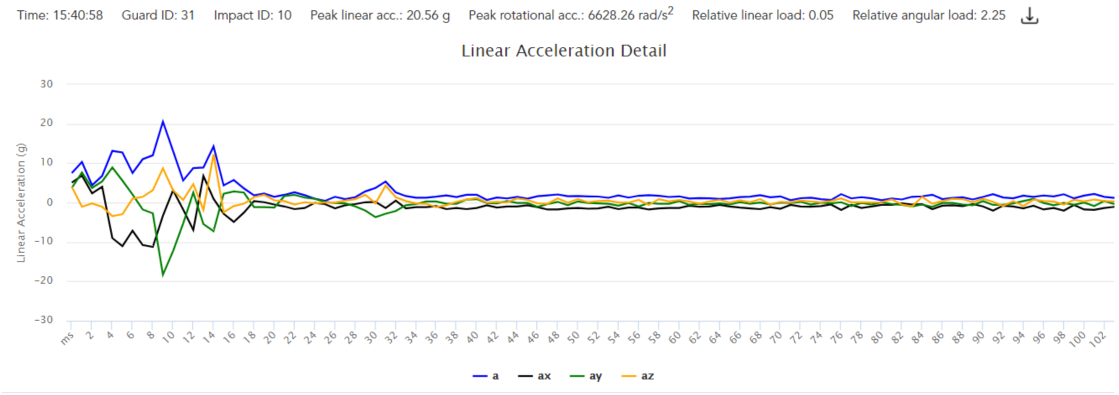


Figure 1: Example of a verified linear acceleration curve pre filtering. The blue line denotes resultant linear acceleration, the black line (ax) shows acceleration of the skull in the x-axis, the green line (ay) represents the y-axis and the yellow line (az)represents the z-axis



Time: 15:40:58 Guard ID: 31 Impact ID: 10 Peak linear acc.: 20.56 g Peak rotational acc.: 6628.26 rad/s^2 Relative linear load: 0.05 Relative angular load: 2.25

Figure 2:Example of a false positive PLA curve pre filtering. The blue line denotes resultant linear acceleration, the black line (ax) shows acceleration of the skull in the x-axis, the green line (ay) represents the y-axis and the yellow line (az)represents the the z-axis

The iMG system did not incorporate filtering with data recording, so raw data was downloaded directly from the system. All impacts were verified via a 3-stage protocol, which included the assessment of video data, waveform quality and comparison against three standard deviations (SD) of peak linear acceleration (PLA) and peak rotational acceleration (PRA) magnitudes) (Figure 3). All data were filtered using a 4th order low-pass Butterworth filter with variable cut-off frequencies determined through residual analysis, as described in Greybe et al., (2020).

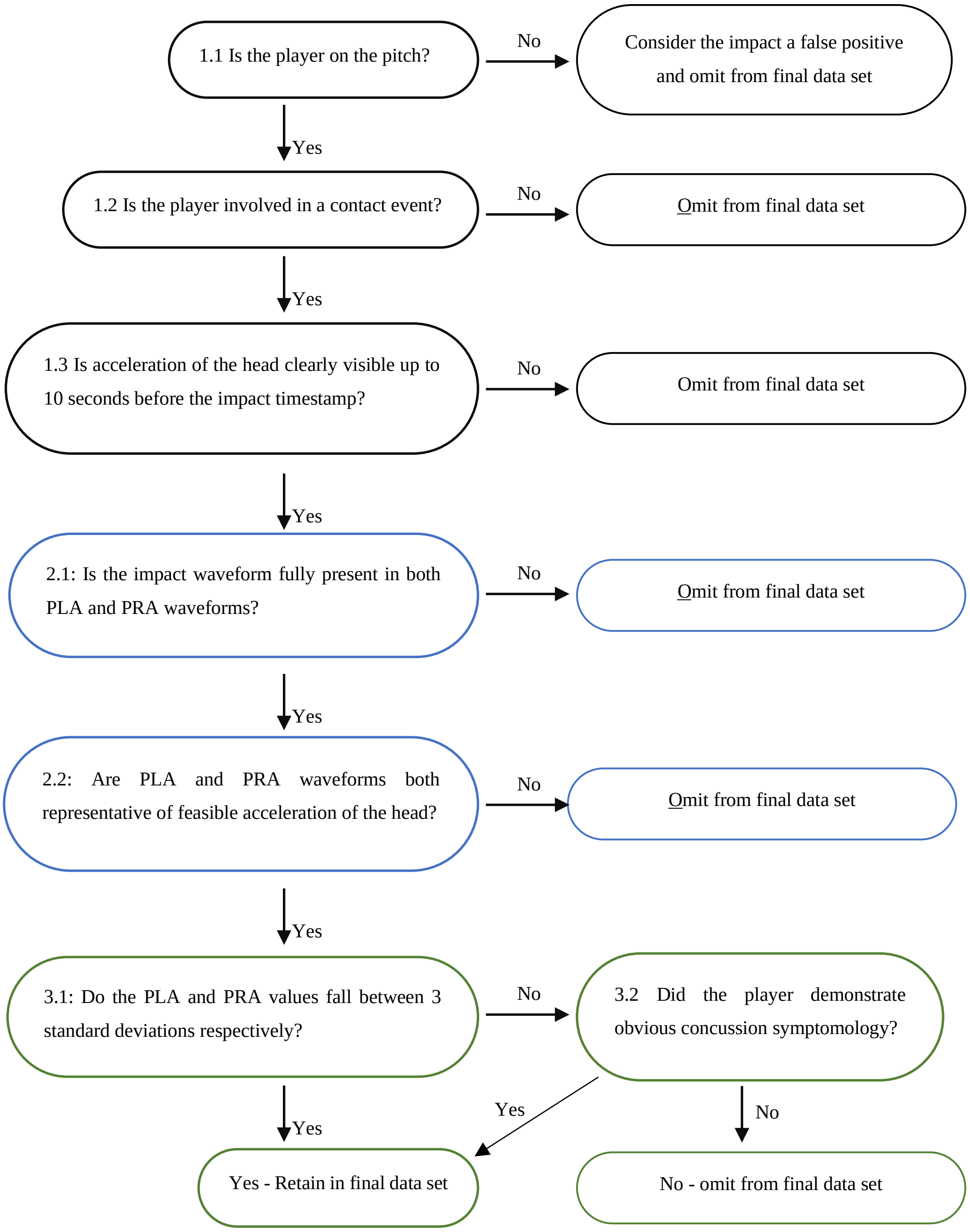


Figure 3: Diagram to illustrate the process of verifying instrumented mouthguard data

PLA magnitudes that dropped below 9.6 g post filtering were omitted from the data set as natural movements (running, jumping) have accelerative values of up to 9.54 g (Ng et al., 2006b). In the final stage of verification, two HAEs exceeded three standard deviations from the mean PLA and PRA values respectively. As both players showed obvious concussion symptomology immediately post-contact, these values were retained in the quantifiable data set. This verification protocol and stringent inclusion criteria minimises the probability of false positives within the data set and improves the accuracy of accelerometer-based research.

3.4 Statistical Analysis

Basic descriptive analysis was completed in Microsoft Excel (Microsoft Corporation 2018) and more complex statistics were performed using IBM SPSS Statistics for Windows, version 26 (IBM Corp., Armonk, N.Y., USA).

All scalar data were tested for normality via a Shapiro-Wilk Test. This test can assess sample sizes up to 2000 and is more powerful than the Kolmogorov-Smirnov Test (Ghasemi & Zahediasl, 2012; Steinskog, Tjøtheim, & Kvamstø, 2007). Where data was normally distributed ($p \geq 0.05$) parametric tests were used. Specifically, independent T tests were used to compare anthropometric data between cohorts whilst one-way analyses of variances (ANOVAs) were used to compare HAE magnitudes across different causes of acceleration and phases of contact.

Where data were not normally distributed, non-parametric equivalent tests were run. Chi-Square tests were used to test for associations between HAE exposure and different playing positions. Kruskal-Wallis H tests were used to determine if impact magnitudes across causes of acceleration were significantly different and Mann Whitney U tests were used to assess if HAE magnitudes across phases were significantly different.

Chapter 4: Results

This results section will be split according to demographic. Results from the collegiate data (player anthropometrics, observed HAEs and quantified HEAs) will be presented first. Results from the elite cohort (player anthropometrics and observed HAEs) are then presented, followed by a comparison of anthropometrics and observed HAEs between cohorts.

4.1 Collegiate Rugby Union

Player Anthropometrics and Experiences

The height and body mass of one collegiate team is shown in (Figure 4) (n = 23). There were no significant differences in these measures between forwards (n = 9) and backs (n = 12) ($p \geq 0.05$). The overall preseason body mass average was 72.0 ± 14.2 kg (range 53.5kg - 104.9 kg). Mean forward body mass was 81.1 ± 18.7 kg and height were 163.5 ± 6.1 cm. Mean back weight was 65.9 ± 6.6 kg and mean height was 163.9 ± 5.9 cm.

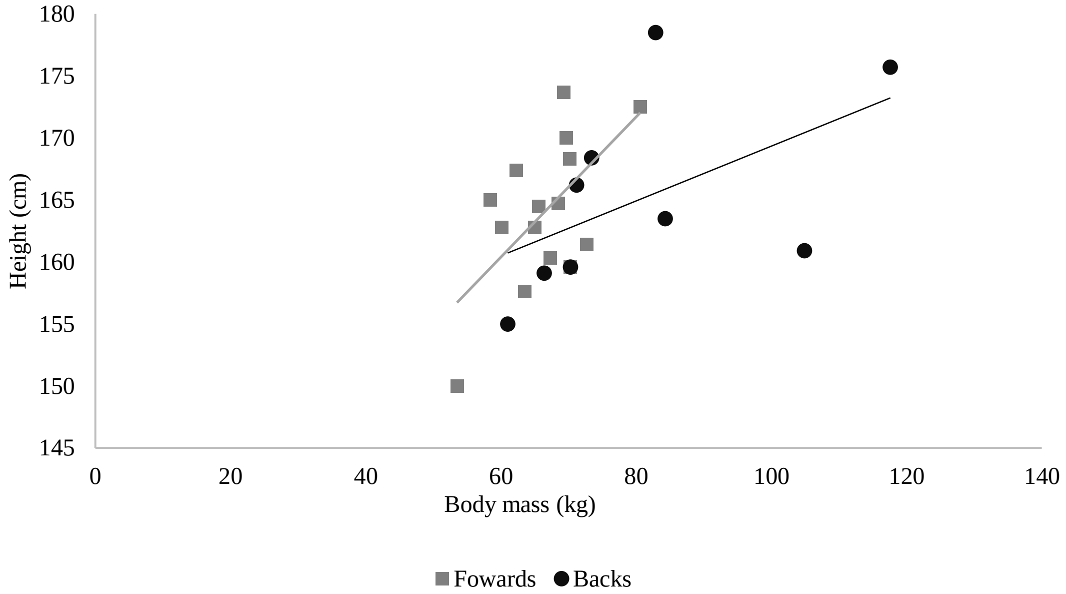


Figure 4: Height and body mass of the collegiate team. Forward data are illustrated as grey squares, Back data are illustrated as black circles

Median player age was 20 (IQR 2). The median number of years playing was 4 (IQR 5.8). Most players started playing rugby for the first time at university (70.6%). Within the collegiate team, three players had been selected for international competition and had been playing rugby for four, eight and ten years respectively. Of the surveyed players, 58.8% had experienced a single and 35.3% multiple concussions during rugby participation, despite their short playing careers.

Collegiate Match Settings

All matches took place on grass pitches, except for one match which was played on an artificial 3G surface. No red cards were given to any player over the season. Only three yellow cards were given: one for a high tackle, one for a mid-air tackle in a line out and one for interfering with play, respectively. As such only two observed HAEs were linked to illegal play. Equipment failure compromised the recording of two games, so that only half the game could be analysed.

Collegiate Cohort Video Results

A total of 690 tackles were observed in the collegiate cohort over the 332 minutes of video footage. The median number of tackles made per match was 66.5 (IQR 36.8). The winning margins across the 2019-2020 season were significantly larger ($p \leq 001$) in the women's division (median 29 points, IQR 33) compared to the comparative men's division (median 8 points, IQR 11.5) (Figure 5).

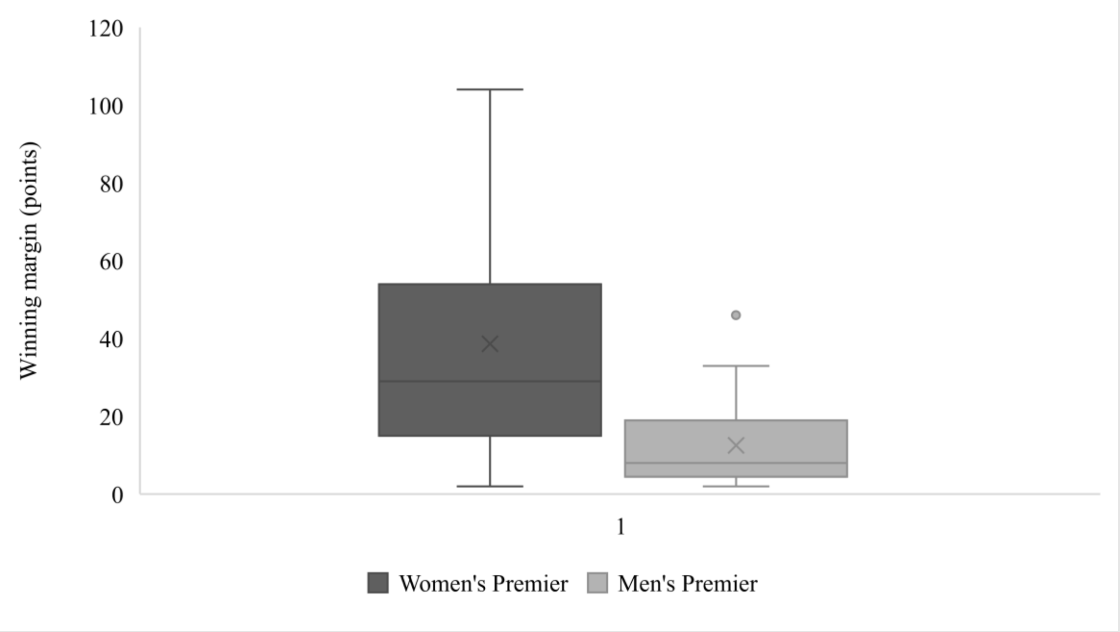


Figure 5: Differences in winning margins between collegiate men's and women's rugby across the season

Data between forwards and backs could only be disaggregated within one collegiate team, as consistent positioning within other teams could not be guaranteed. Forwards made 263 tackles and 262 carries over the three full and two half games analysed for observed HAE, whereas backs made 123 tackles and 103 carries. A discrepancy is seen between total number of tackles and number of times players made tackles or carries as 26.4% of tackles were made by multiple players.

Analysis of Observed Head Acceleration Events in the Collegiate Cohort

Over the 332 analysed playing minutes, 690 tackles and 439 HAEs were observed. On average, one HAE was observed every 48 seconds. A greater number (252) of HAEs were observed in ball carriers than in tacklers (187). A carrier HAE was observed in 36.5% of all carries and a tackler HAE in 27.1% of all tackles. The rate of carrier HAE was one every 1min 18s. The rate of tackler HAE was one every 1 min 48s of play. No significant difference was found between the percentage of contact events that caused an HAE in forwards or backs (*p*=0.815), (Figure 6). Forwards completed double the number of contact events to backs; forwards made one tackle every 1min and 18s and one carry every 1min and 18s, whereas backs made one tackle every 2min and 42s and one carry every 3 min and 12s.

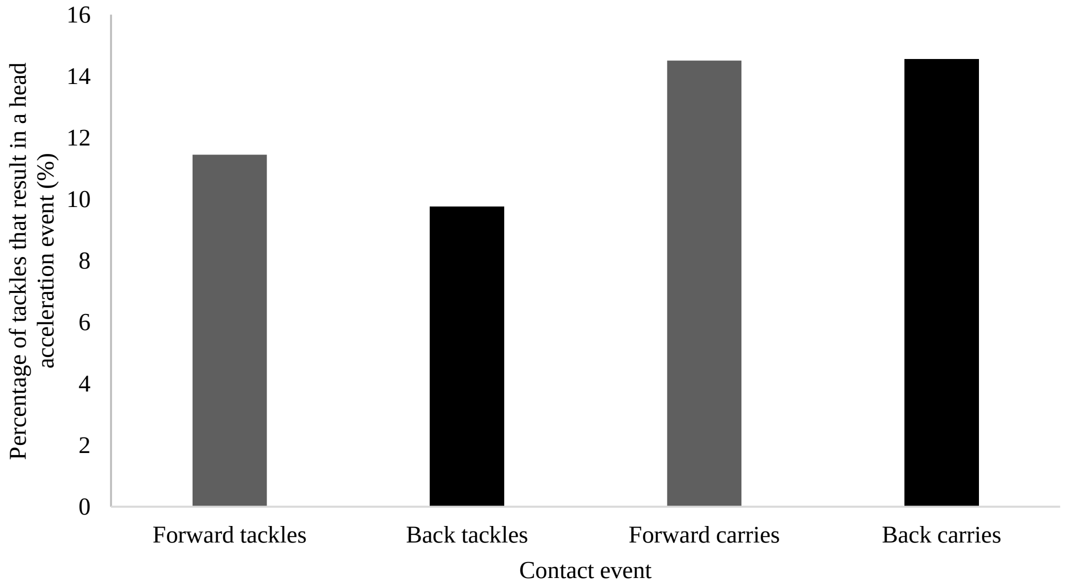


Figure 6: Percentage of tackles that result in a tackler head acceleration event and percentage of carries that result in a carrier head acceleration event

Causes of Collegiate Head Acceleration events

In the collegiate game, the most common cause of HAE overall was contact between the head and another player (46.3%), followed by head-to-ground contact (35.5%), indirect impacts (15.7%) and other causes (2.8%). In the 'other' category, eight HAEs were caused by the carrier handing-off the tackler (a legal action where the ball carrier may push the tackler away using the palm of their hand (World Rugby, 2020a), one involved head-to-ball contact and one involved a fall not linked to a contact event.

The most common cause of tackler HAE was contact between the tackler's head and the body part of another player (54%), followed by contact between the tackler's head and the ground (31%), indirect impacts (8.6%) and other causes (5.4%). In the carrier, the most common cause of HAE was player-to-player contact (40.5%), followed by head-to-ground contact (38.5%). Indirect mechanisms accounted for 21% of carrier HAE (Figure 7).

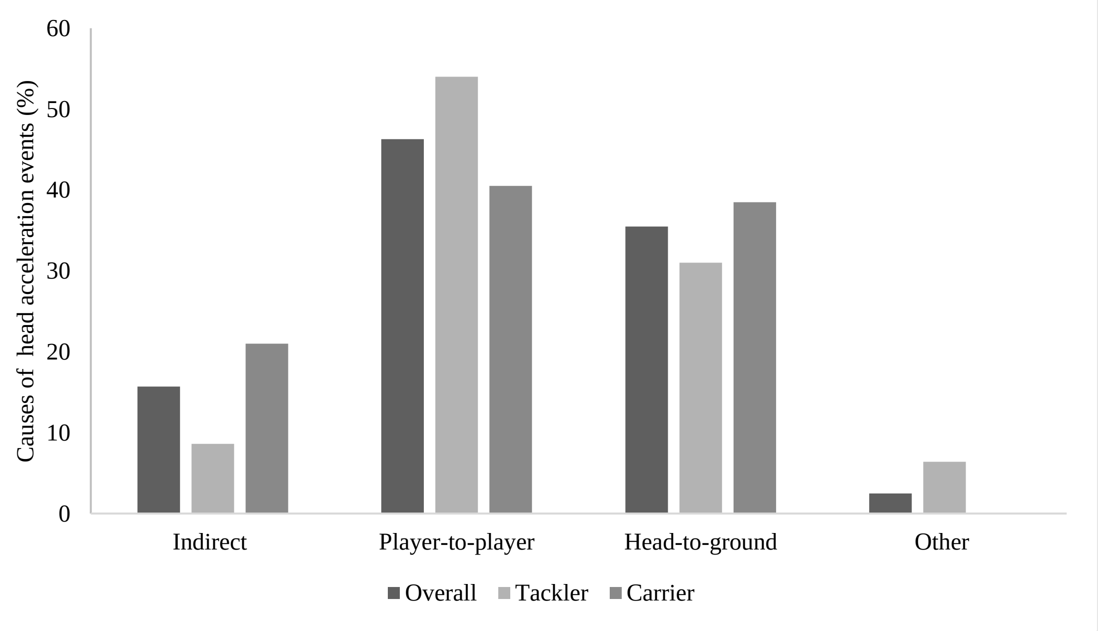


Figure 7: Causes of collegiate head acceleration events split into tackler and carrier

Contact with hard body parts accounted for 95.8% of the HAEs that result from player-to-player contact, while soft body parts accounted for 4.2%. The soft body parts involved in contact were the chest (0.5%), upper arm (0.9%), torso (0.9%) and thigh (1.9%). The most common hard body part involved in contact was the knee (20.6%), followed by the hip (19.6%), shoulder (15.9%), boot of another player (13.1%), head (11.7%), elbow

(5.6%) and shin (4.2%) (Figure 8). Carrier hand-offs the tackler accounted for 3.7% of player-to-player HAEs.

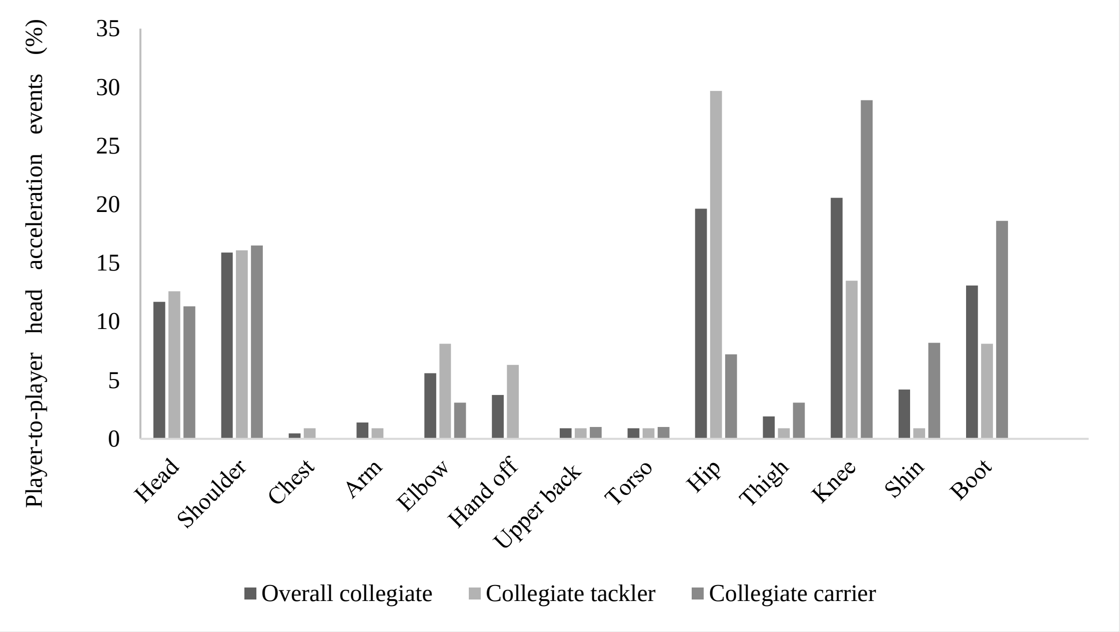


Figure 8: Body parts contacted in tackler and carrier player-to-player head acceleration events

Whiplash Style Head Kinematics

Novel head acceleration kinematics were observed in collegiate players and were present during 51.2% of all collegiate HAEs. During contact, control of the cervical musculature appeared to be lost. Consequently, the player was unable to stabilise the neck during a contact event and accelerative forces were transmitted through the neck into the head (Figure 9). These whiplash style head kinematics (WSHK) were observed only in head-to-ground HAEs (70%) and indirect HAEs (30%). The carrier was more susceptible to WSHK and experienced 67.2% of total WSHK compared to the tackler, who experienced 32.8%. WSHK were most commonly observed during the fall from contact (Phase 2, 85%), relative to initial contact (Phase 1, 15%). WSHK were not present in Phase 3. These kinematics were present in 13.8% of tackles and in 17.7% of carries.

Figure 9: Video stills showing a collegiate ball carrier experiencing a head-to-ground head acceleration event

Head Acceleration Events by Contact Phase

HAEs most commonly occurred during Phase 2 as the player fell from contact (56.2%), followed by during Phase 1 (25.5%) and were least common in Phase 3 (15.1%). A similar pattern was seen between tacklers and carriers and in both forwards and backs (Figure 10).

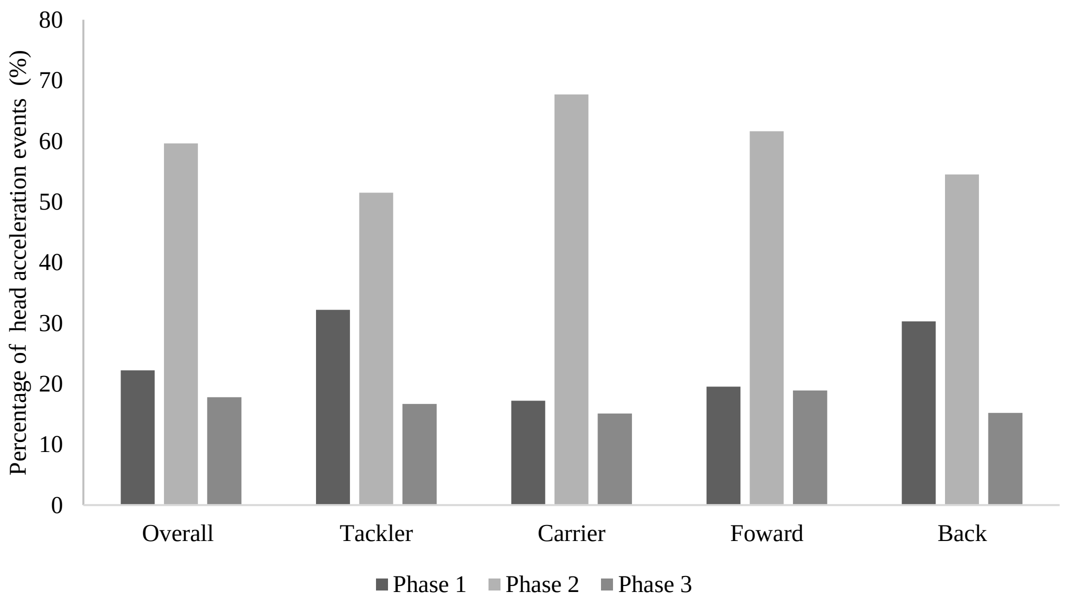


Figure 10: Percentage of head acceleration events that occur in each phase

The area of the body contacted in player-to-player HAEs differed by phase of impact. In Phase 1, 61% of HAEs resulted from contact between the head and body parts above the hip. In Phase 2, only 13% of contacts were above the hip, while in Phase 3, only 7%

were above the hip (Figure 11). When contact was made between the heads of two players, 88.4% occurred in Phase 1, with the remaining 11.6% occurring in Phase 2.

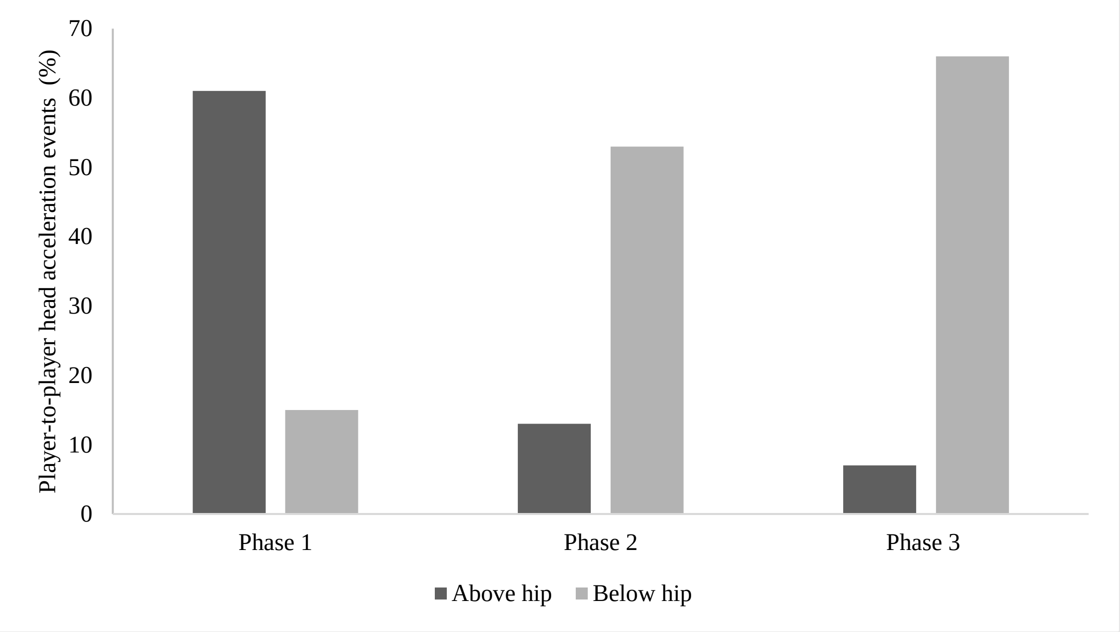


Figure 11: Contacted body part in collegiate player-to-player head acceleration events per phase

Variation of Head Acceleration Incidence Within the Collegiate Team

When the contact events and HAE frequency were normalised to an 80-minute match, considerable variation was seen in the number of tackles, carries and HAEs between players (Figure 12). The median number of tackles per player per match was 5 (IQR 4) and the median number of carries was 5 (IQR 4). The median number of HAEs experienced per player per match was 4 (IQR 11). The number of HAEs had a significant, positive correlation to the number of contact events performed by each player (*p* <0.01, Spearman's rho correlation coefficient 0.785).

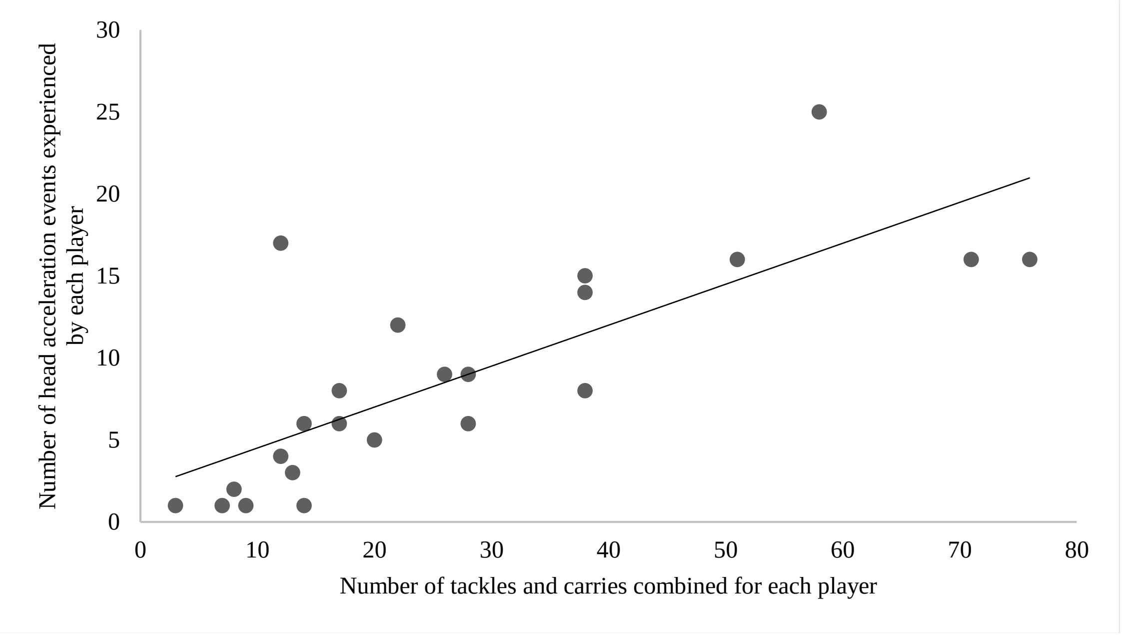


Figure 12: Correlation between the number of head acceleration events and the number of tackles and carries performed per player.

4.2 Quantified Head Acceleration Events: Head Impact Telemetry System

The iMG system recorded 89 quantified HAEs that passed strict video and waveform verification. A 10 g threshold was set for impact recording, however, filtering brought 16 values to below 9.6 g. Only impacts greater than or equal to 9.55 g were retained in the data set leaving 73 HAEs recorded within tackles, rucks and one maul (Figure 13).Median PLA was 11.96 g (IQR 7.27 g) and median PRA was 4291.66 rad/s^2, (IQR 646.86 rad/s^2). Of these 73 HAES, 38 occurred in a tackler, 23 in a ball carrier, 11 within a ruck and 1 in a maul. Forward players recorded 43 HAEs, whilst backs recorded 30 HAEs.

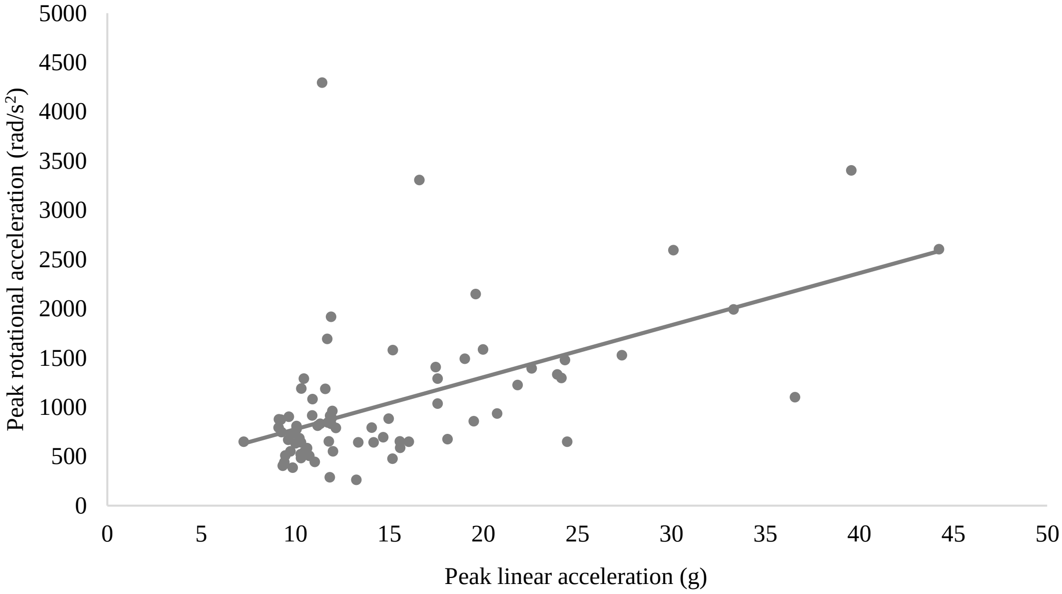


Figure 13: Magnitude of all verified head acceleration events

Quantified Head Acceleration Events by Cause of Acceleration

No verified HAEs were recorded within lineouts or scrums. PLA or PRA HAE magnitudes were not significantly different between tackles, carries and rucks (PLA *p*=0.528, PRA *p*=0.340) or between different causes of HAE (PLA *p*=0.445, PRA *p*=0.282) (Figure 14, Figure 15). HAE magnitudes did not significantly differ across phases (PLA *p*=0.339, PRA *p*=0.611).

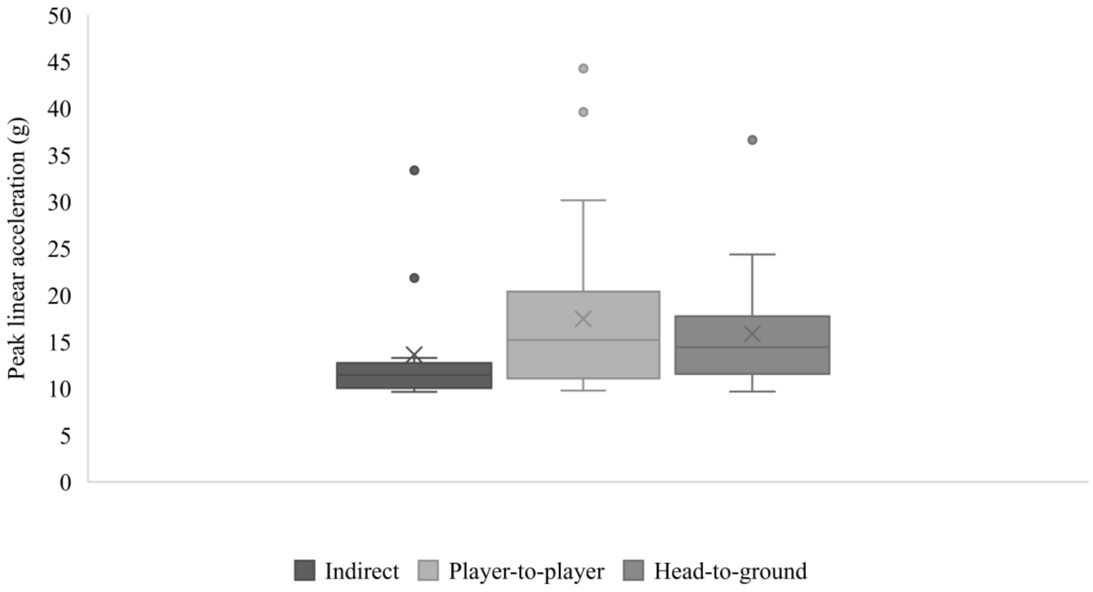


Figure 14: Peak linear acceleration by cause of head acceleration event

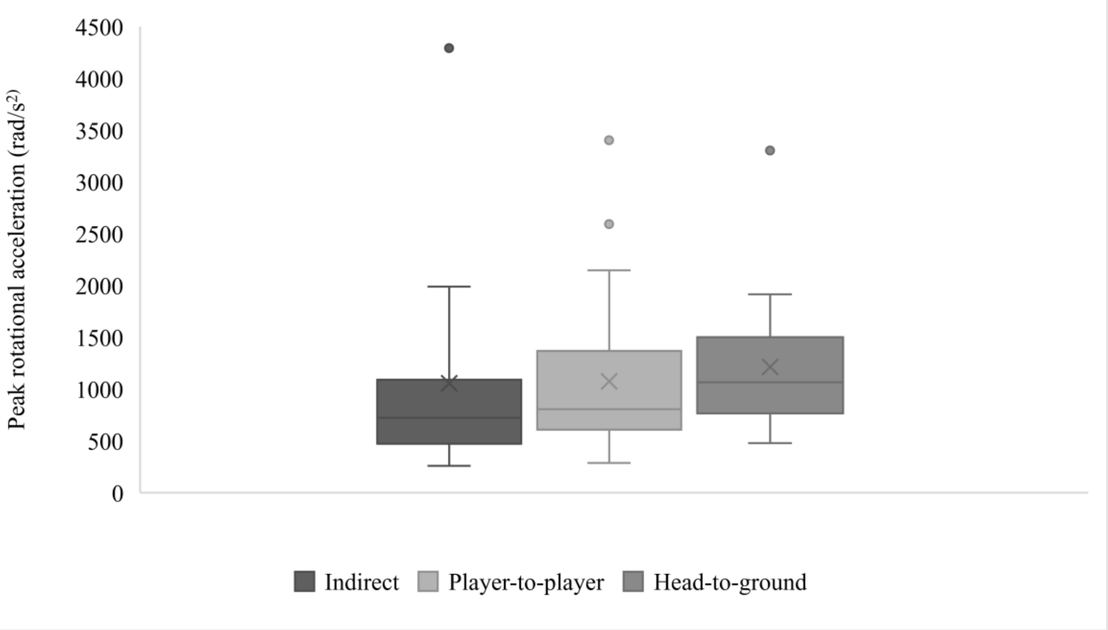


Figure 15 Peak rotational acceleration by cause of head acceleration events

HAE magnitudes did not differ significantly across phases (PLA p=0.110, PRA p=0.175). The PLA or PRA did not significantly differ by direction (PLA p=0.277, PRA p=0.597).

Magnitude of HAE was not significantly different between head, shoulder, hip or knee contact (PLA p=0.172, PRA p=0.690 (Figure 16, Figure 17). The small sample of quantified player-to-player contacted prevented further statistical analysis.

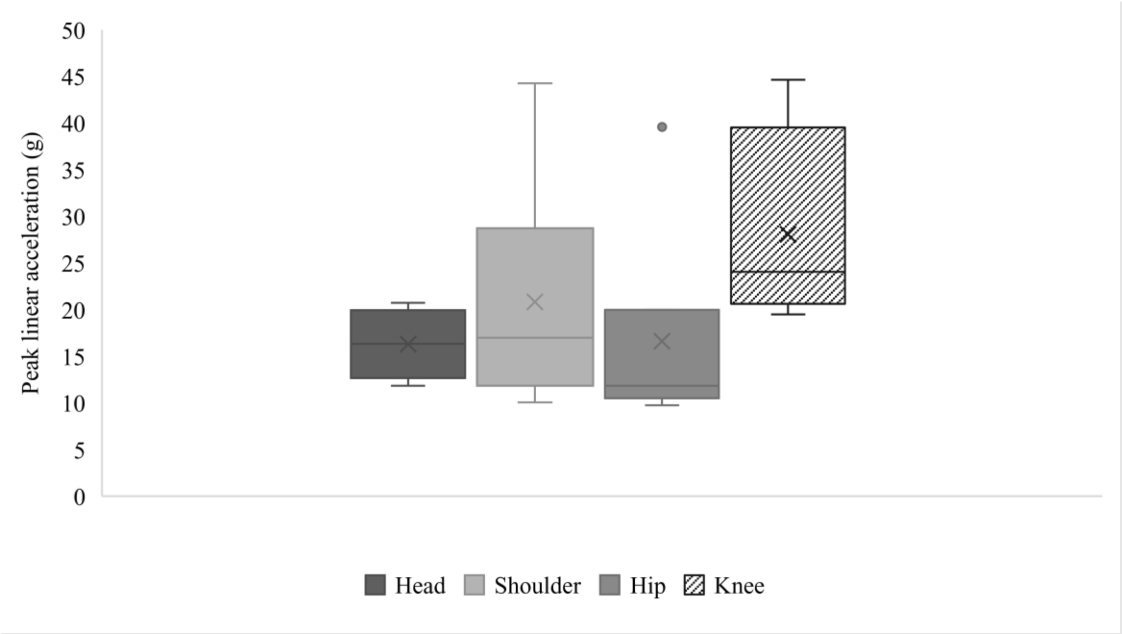


Figure 16: Peak linear acceleration of player-to-player head acceleration events by body part

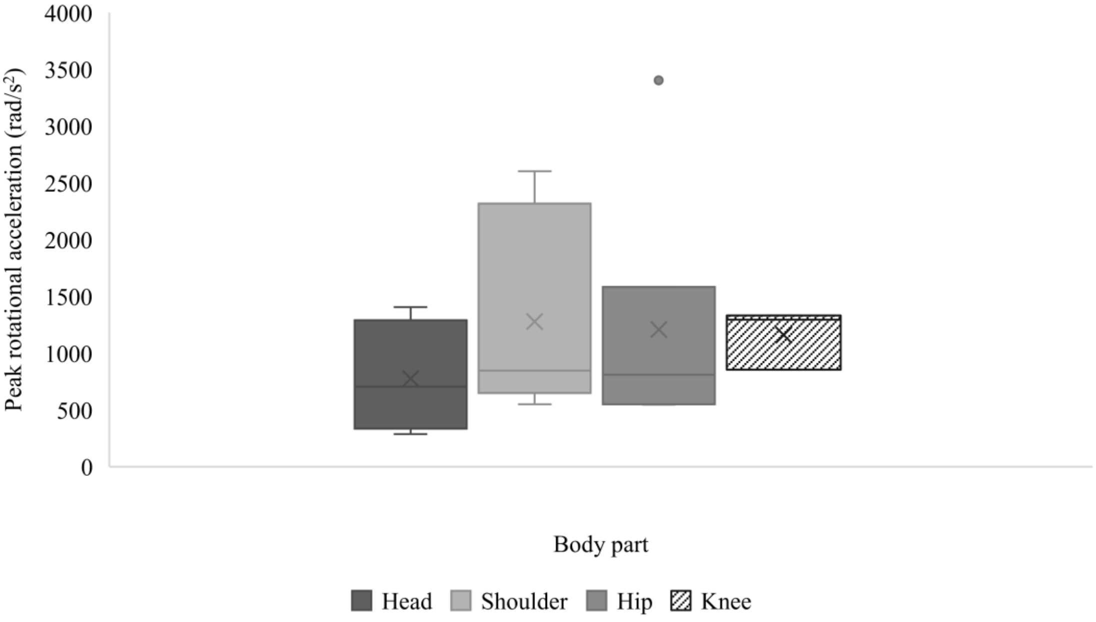


Figure 17: Peak rotational acceleration of player-to-player head acceleration events by body part

Quantified Head Acceleration Events Recorded in the Ruck

The median PLA value for HAEs recorded during rucks was 10.5 g, (IQR 7.14 g) and the median PRA was 647.55 rad/s^2 (IQR 390.9 rad/s^2). The PLA and PRA of the single HAE recorded in a maul were 19.61 g and 2148.03 rad/s^2 respectively.

Quantified Head Acceleration in Tacklers and Carriers

The median PLA value recorded in tackler HAEs was 12.06 g (IQR 8.2) and the median PRA was 864.87 rad/s^2 (IQR 554.3). The median ball carrier HAE PLA was 11.83 g (IQR 5.01) and the median PRA was 817.39 rad/s^2 (IQR 665.95). No significant differences in were found between the HAE magnitude experienced by carriers or tacklers (PLA p=0.094, PRA p=0.405), or between forwards and backs (PLA p=0.796, PRA p=0.782).

Whiplash Style Head Kinematics

HAEs with WSHK had a median PLA of 12.0 g (IQR 6.5) and a median PRA of 843.0 rad/s^2 (IQR 763 rad/s^2), (Figure 18). HAE magnitudes did not differ significantly between WSHK caused by indirect or head-to-ground mechanisms (PLA p=0.09, PRA p=0.08)

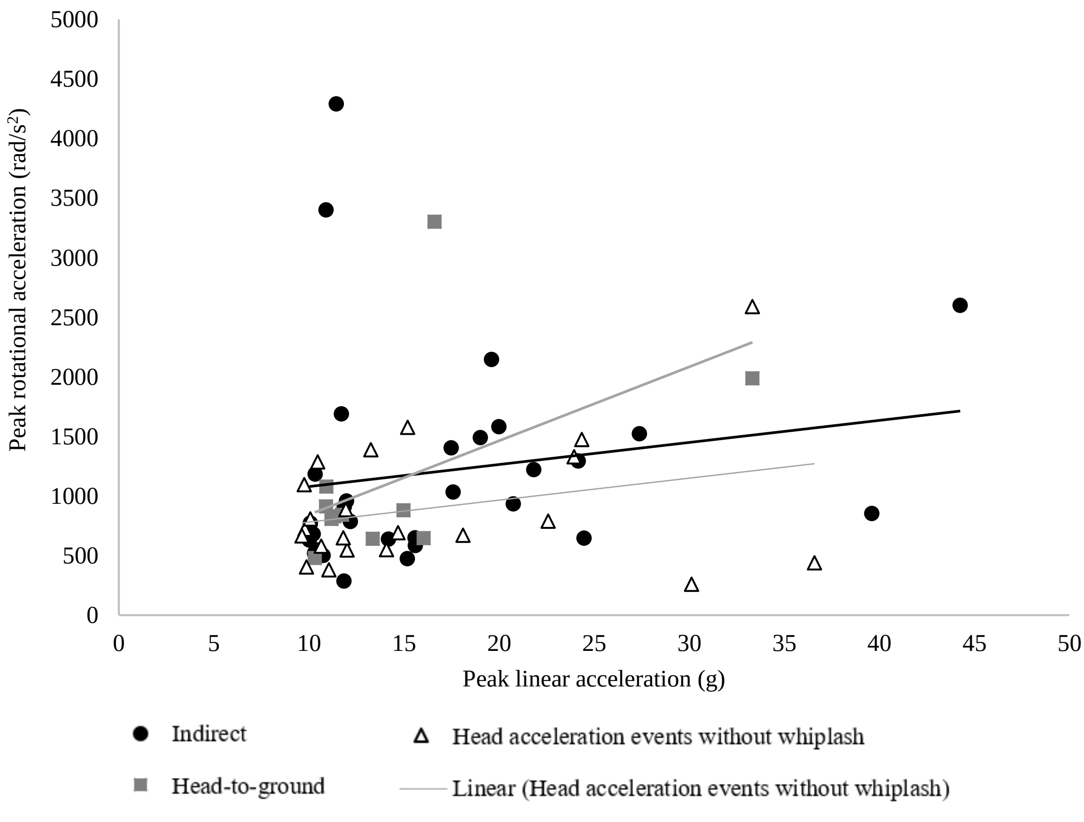


Figure 18: Peak linear acceleration and peak rotational acceleration of collegiate head acceleration events with and without whiplash-style head kinematics

4.3 Elite Rugby Union

Player Anthropometrics and Experiences

The height and body mass of elite players is shown in (Figure 19). The overall mean body mass was 79.2 ± 13.4 kg, (range 55.9 kg - 125.0 kg). Elite forwards had significantly greater body mass and height ($p \leq 0.001$, $p \leq 0.001$) than elite backs. The mean forward body mass was 86.8 ± 11.8 kg and the mean back body mass was 69.4 ± 7.8 kg. The mean forward height was 172.6 ± 7.1 cm and the mean back height was 169.1 ± 7.3 cm. Body mass did not differ significantly between elite teams, with the exception of the WN1 team who had a greater body mass than the WR4 team ($p \leq 0.05$).

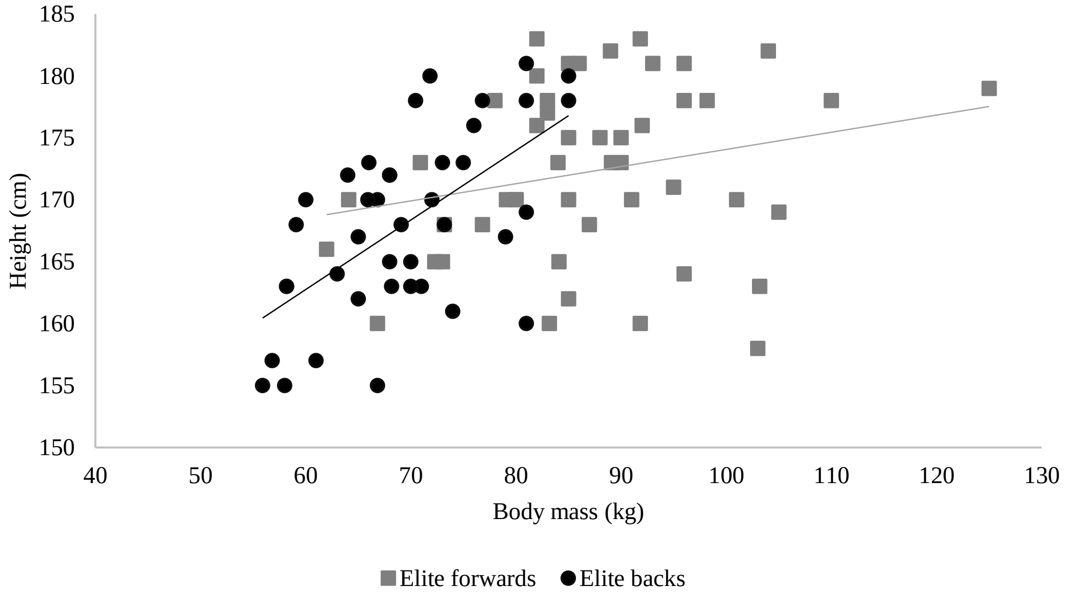


Figure 19: Height and weight of elite players

Mean elite player age was 26 ± 3.6 years (Figure 20). The WN1 team had the oldest mean age (27.2 years ± 3.9), followed by WN4 (26.9 years ± 2.7), WN2 (26.5 years ± 3.5) and WN9 (23.8 years ± 3.2). In the WN2 team, more detailed biographies reported the age at which players joined the sport. In these players (n=16), the median age for joining rugby was 10 years (IQR 5) and range was 5 to 21 years. Most players (69%) in the WN2 team began playing under the age of ten and the remaining 31% began playing between the ages of 11 and 21.

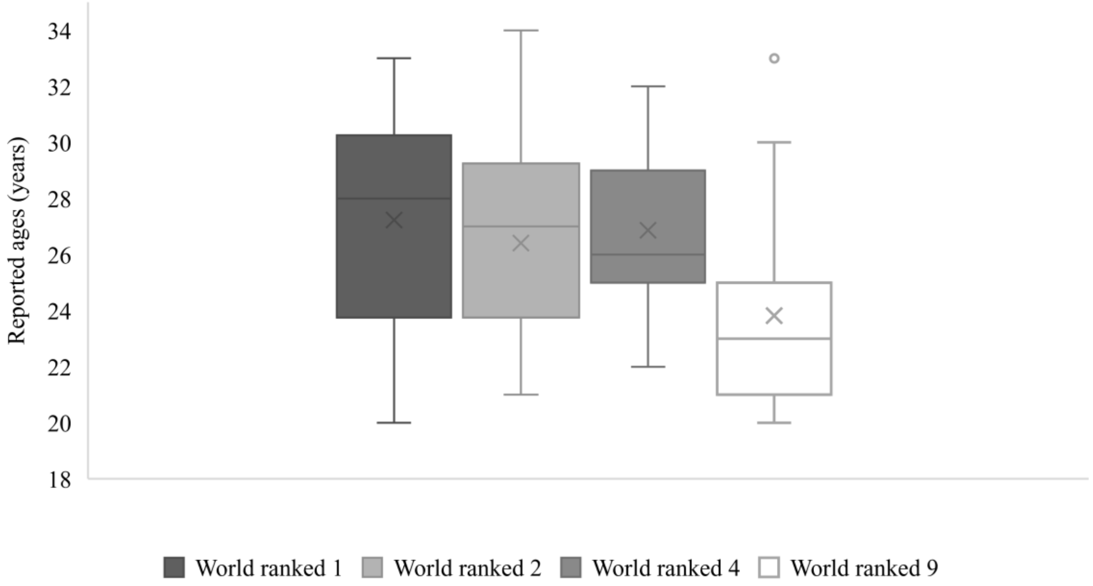


Figure 20: Reported ages of elite players by team

Elite Match Settings

In total, 162 minutes of elite game play were analysed over two international matches. Match A was played between the WN1 and WN2 teams, won by WN1 by 15 points. Over the match, 160 tackles were recorded between teams. Of these, 147 were of sufficient video quality to allow observation of HAEs. The match took place on a grass pitch and only one player received a yellow card outside of a contact event. Match B was played between WN9 and WN4, won by WN4 score of 50. In Match B, 176 tackles were recorded and 147 were of sufficient video quality to allow observation of HAEs. The match was played on an artificial surface and no players received red or yellow cards.

As of March 2020, the WN4 were placed second out of six teams and WN9 were placed sixth in the Six Nations tournament. Match winning margins over the 2019 and 2020 tournament were significantly larger ($p<0.01$) in the women's matches compared to the men's (Figure 21). The median winning margin in the women's tournament was 24 points (IQR 32.5, range 64), whereas the median winning margin in the men's tournament was 11 points (IQR 7, range 40).

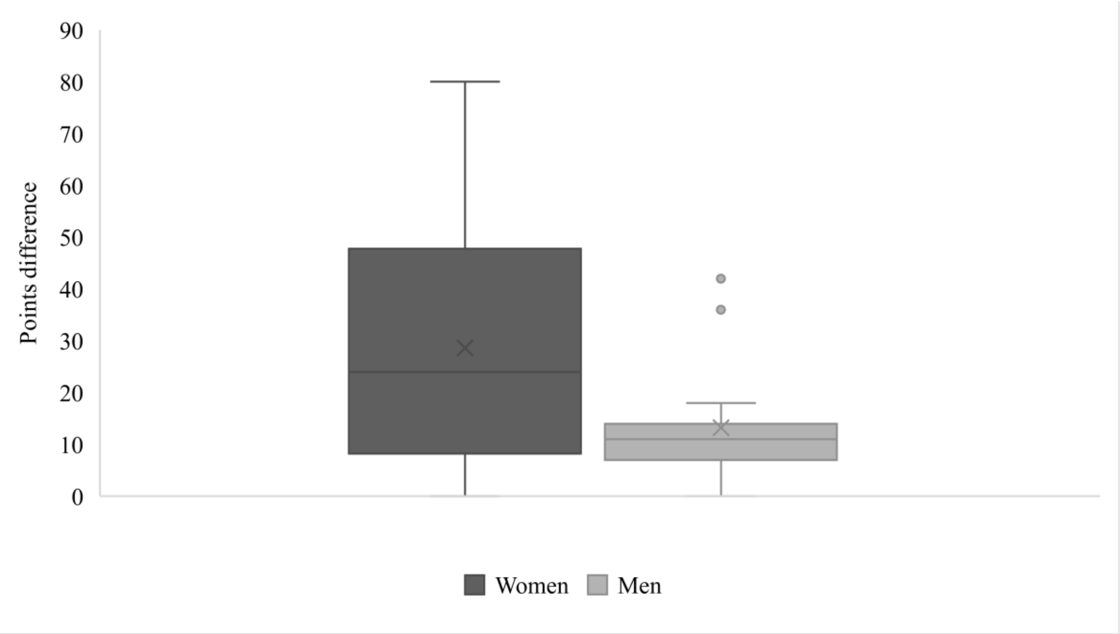


Figure 21: Winning margins between the men and women's 2019 and 2020 6 Nations Tournament

Observed Head Acceleration Events in Elite Players

Over 162 playing minutes, 103 HAEs were observed in the 294 tackles analysed. On average, one HAE was observed every 2 min and 54 seconds. Ball carriers experienced a greater number of HAEs (58) compared to tacklers (45). The percentage of HAEs observed per tackle did not linearly decrease as world ranking increased (Figure 22). The greatest number of HAEs were experienced by the WN2 team (37), followed by WN1 (28), WN9 (25) and WN4 (13). The WN2 performed the highest number of tackles (80), followed by WN9 (75), WN4 (72) and WN1 (67). Rate of elite carrier HAE was one every 1 min and 48 seconds and elite tackler HAE was one every 2 min and 30 seconds. A tackler HAE was present in 14.6% of tackles, while a carrier HAE was present in 18.7% of carries.

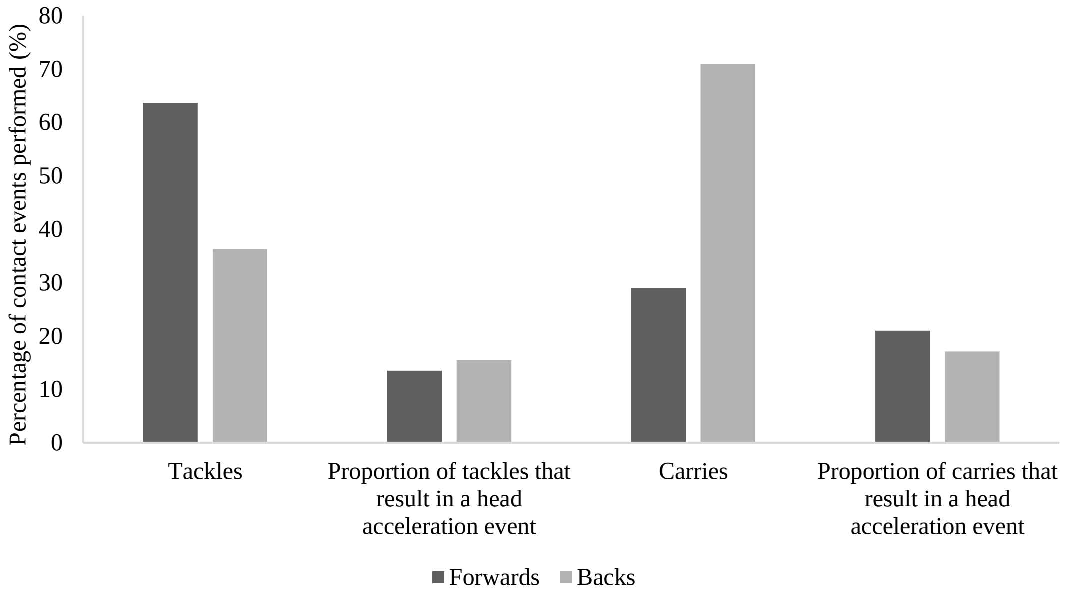


Figure 22: Percentage of contact events performed by forwards and backs and the proportion of events that involve a head acceleration event

Players could be identified as forwards or backs in 91.7% of tackles. Forward players performed 1.7 times more tackles than backs (n=193 and n=110 respectively). Backs completed 2.4 times the carries of forward players (n=62 and n=152) respectively, (Figure 23). No significant difference was found between the propensity of forwards or backs to experience an HAE in tackles (*p*=0.634) or carries (*p*=0.881). On average, forwards completed a tackle every 48 seconds and a carry every 2 min and 38 seconds. Backs completed a tackle every 1 min and 30 seconds and a carry every 54 seconds.

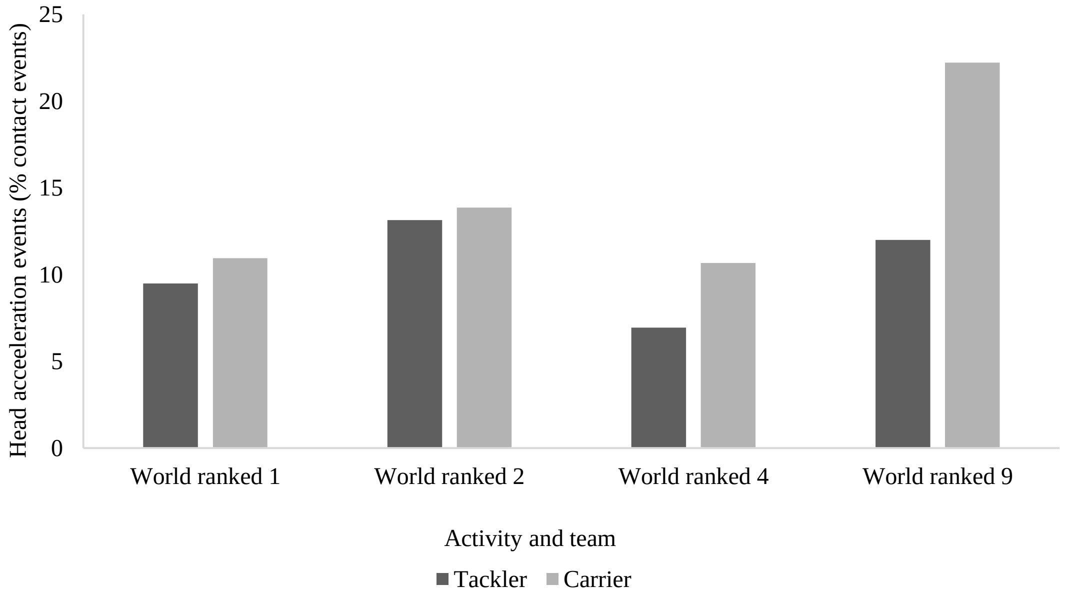


Figure 23: Percentage of contact events that resulted in a head acceleration event

Causes of Head Acceleration Events in the Elite Players

Causes of HAEs are illustrated in Figure 24. The most common cause of HAEs in elite players was contact between the head and another player (76.6%), followed by indirect mechanisms (9.9%), head-to-ground (6.3%) and other (7.2%). All HAEs categorised as other were the result of the ball carrier handing-off the tackler.

The most common cause of elite tackler HAE was player-to-head contact (81.4%), followed by other (9.2%), indirect (4.7%) and head-to-ground (4.7%). In the carrier, player-to-player contact was most common (77.8%), followed by indirect (14.8%) and ground (7.4%). The carrier was 3.1 times more likely to experience an indirect HAE and was 1.5 times more likely to experience a head-to-ground HAE.

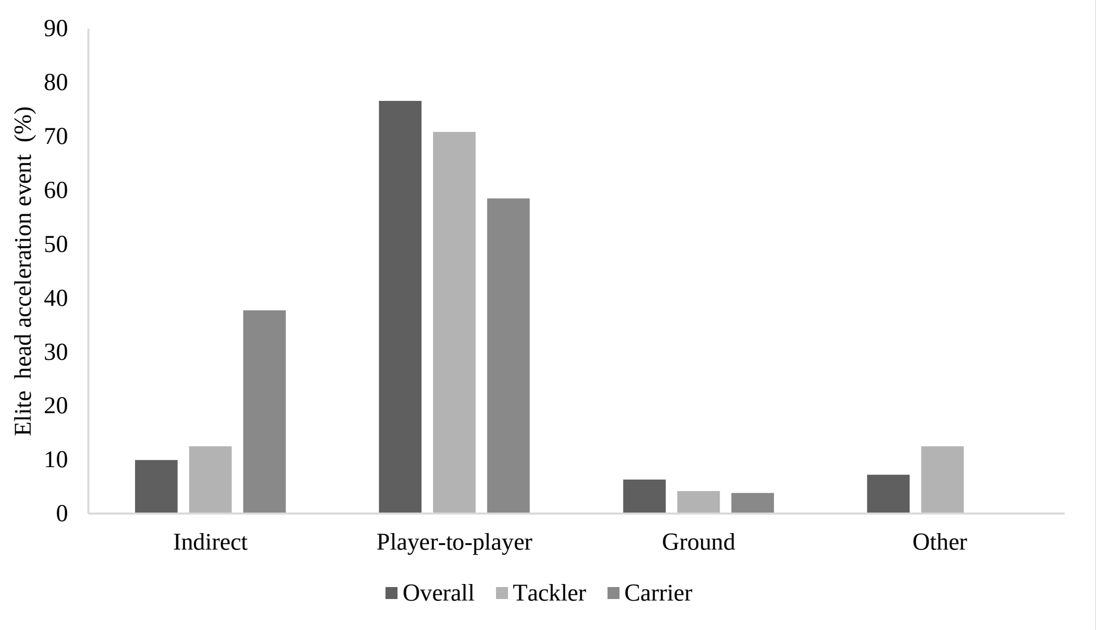


Figure 24: Causes of elite head acceleration events split into tackler and carrier

Contact with hard body parts accounted for 97.2% of all player-to-player HAEs (Figure 25). The head was the most common body part contacted (24.4%) followed by the knee (21.8%), shoulder (14.1%), boot (11.5%). Carrier hand-offs to the tacklers head accounted for 9.0% of player-to-player HAEs. Contact with the arm, elbow and hip was equally prevalent, with each accounting for 5.1% of player-to-player HAEs. The chest (2.6%) and arm (5.1%) were the only soft body parts contacted and contact with the shin was least prevalent (1.3%).

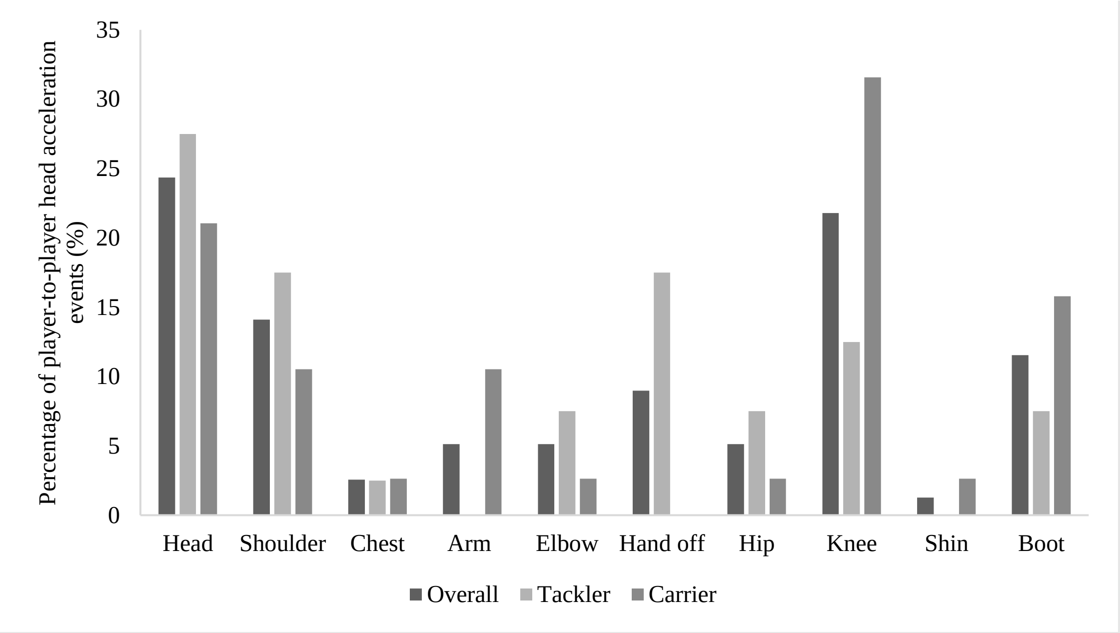


Figure 25: Body parts contacted in elite player-to-player head acceleration events

Whiplash Style Head Kinematics

WSHK were observed in 16.2% of HAEs experienced by elite players. The majority of WSHK (58.8%) were seen in head-to-ground HAEs, with 41.2% in indirect HAEs. WSHK were most commonly seen in Phase 1 (56.2%), followed by Phase 2 (43.8%). No WSHK were observed in Phase 3. WSHK were present in 4.2% of tackles overall and incidence decreased as world ranking increased. In the WN1 team, 2.4% of all tackles and carries resulted in WSHK. This increased to 3.7%, 4.3% and 6.3% for the world ranked 2nd,4th, 9th teams, respectively (Figure 26, Figure 27). WSHK were more commonly seen in carriers (accounting for 76.7% of incidence) than tacklers (23.3%). No significant association was found between the direction of fall and likelihood of carrier WSHK (p=0.370).

Although not quantified, several elite players seemed to control the way they fell. If players began to fall backwards, they often twisted to land on their front or side, rather than onto their backs. Some elite players appeared to contract their abdominal muscles as they fell backwards to keep the torso off the ground, whereas others performed a rolling fall, particularly in faster tackles.

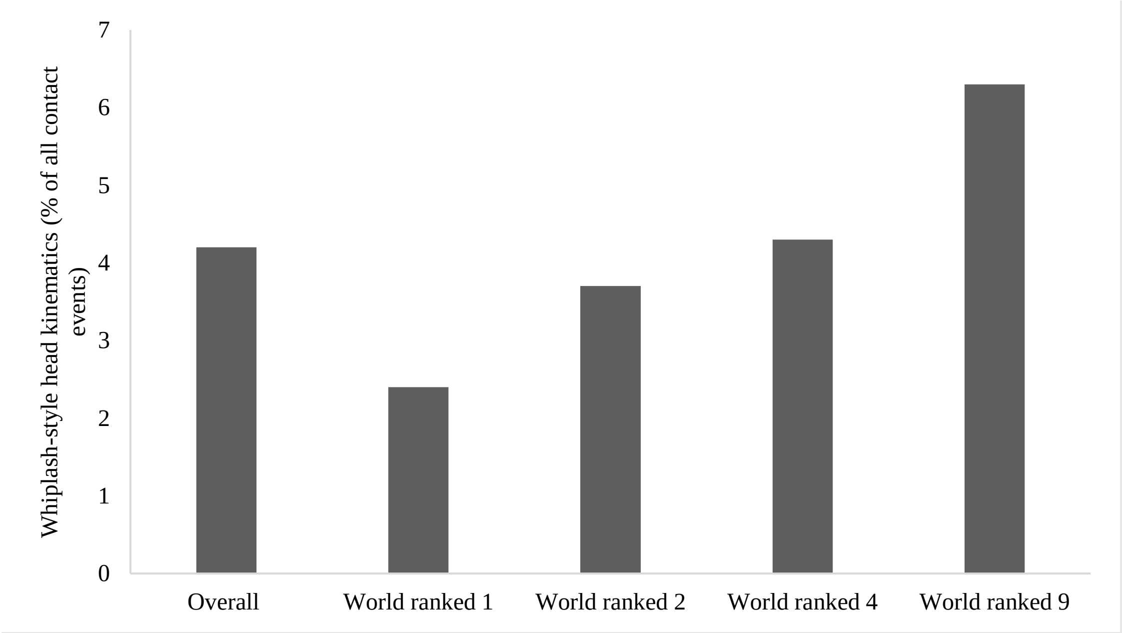


Figure 26: Incidence of whiplash-style head kinematics across elite teams

Figure 27: Example of whiplash style head kinematics in elite players. The player in blue was able to control her neck as she fell to prevent a head-to-ground impacts, whereas the player in red did not stabilise her head as she fell.

Head Acceleration Events by Contact Phase

HAEs were most prevalent in Phase 1 (52.6%), followed by Phase 2 (33.2%) and were least prevalent in Phase 3 (14.2%). A similar pattern was seen between forwards and backs and in tacklers and carriers (Figure 28: Percentage of head acceleration events experienced in each phase).

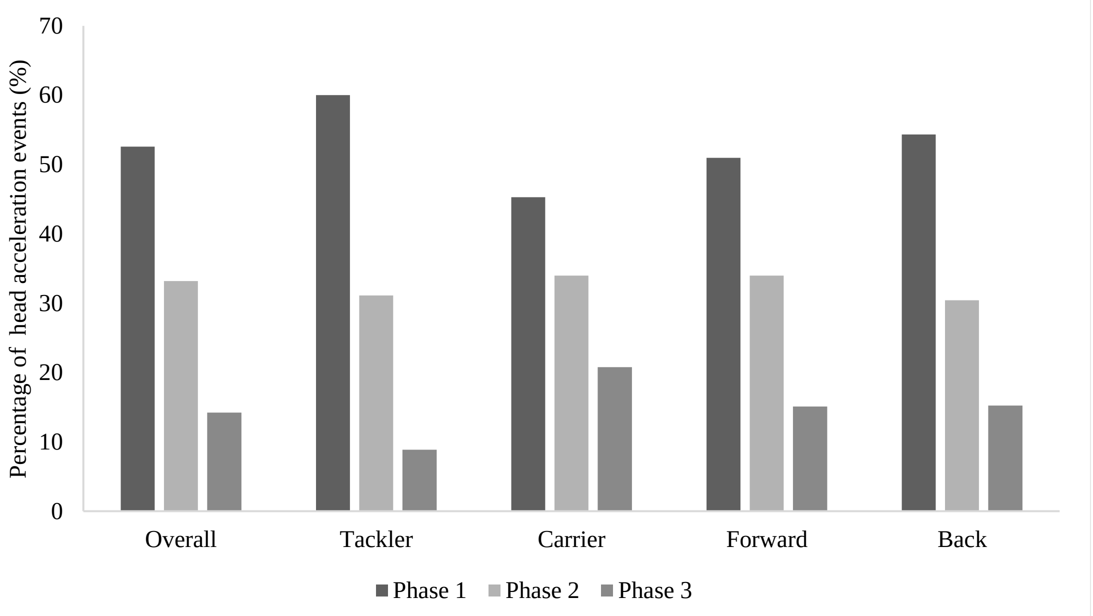


Figure 28: Percentage of head acceleration events experienced in each phase

The part of the body contacted in player-to-player HAE differed by phase. In Phase 1 96% of player-to-player HAEs resulted from contact with a body part above the hip whereas in Phase 3 no HAEs resulted from contact above the hip (Figure 29). All HAEs caused by head-to-head contact occurred in Phase 1.

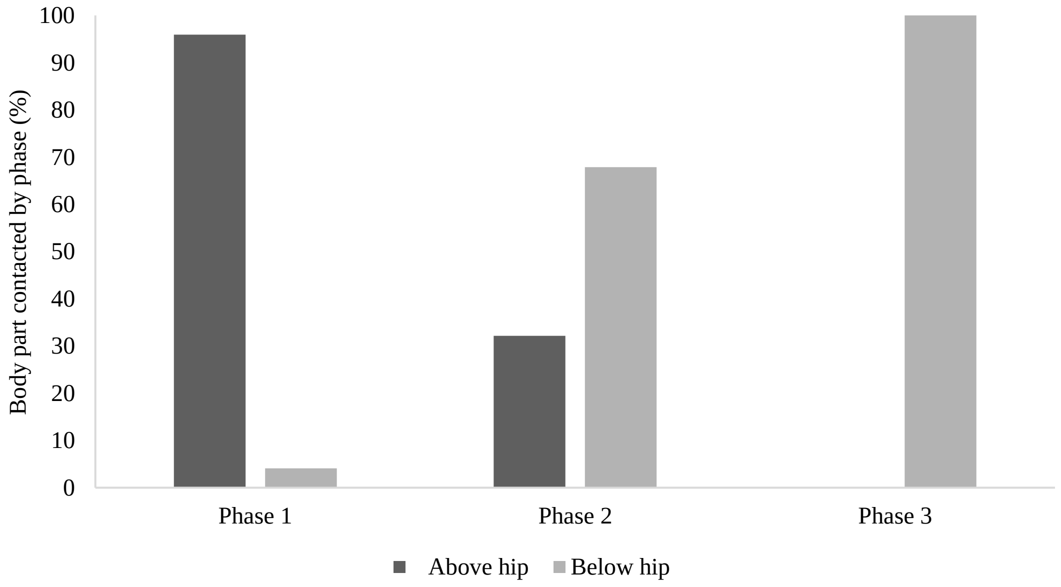


Figure 29: Body part contacted in player-to-player contact by phase

Variation of Head Acceleration Event Incidence Between Elite Players

The median number of tackles performed per player per match was 3 (IQR 5, range 20) and the median number of carries performed was 3 (IQR 3, range 13). The median number of HAEs experienced per player per match was 0.3 (IQR 1.1, range 25) when normalised over an 80-minute game. The median number of HAEs was moderately correlated with the number of tackles and carries performed (Spearman's rho correlation coefficient 0.504, *p*<0.01) (Figure 30).

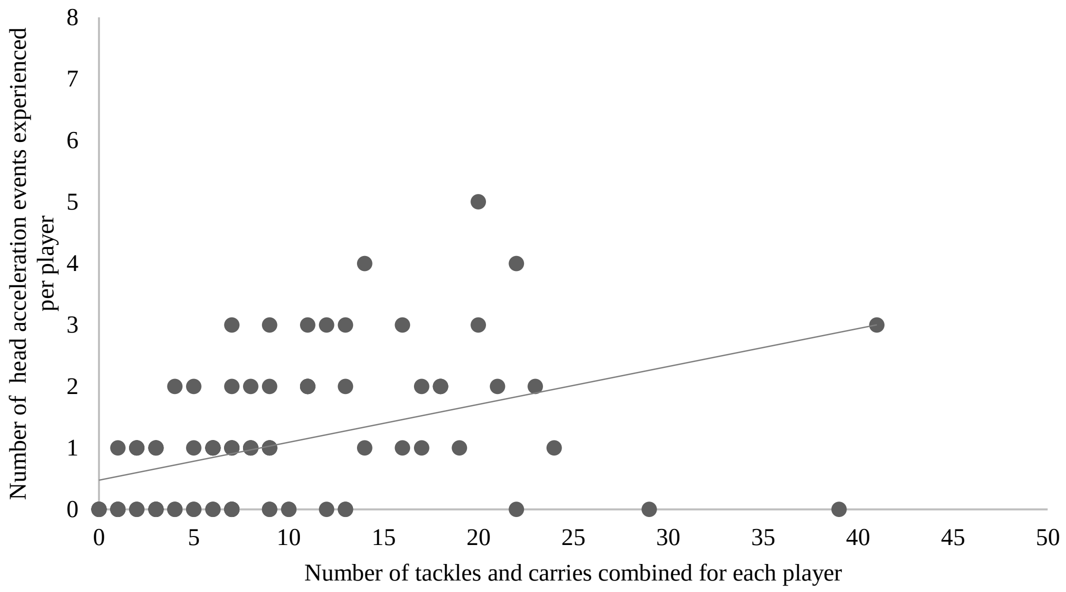


Figure 30: Correlation between the number of head acceleration events and the number of tackles and carries performed per player (normalised to an 80-minute game).

4.4 Comparison Between Collegiate and Elite Rugby Union

Player Anthropometrics and Experiences

Elite players were significantly taller (*p*<0.001) and heavier (*p*<0.001) than collegiate players (Figure 31). Both the collegiate and elite teams had a wide range in body mass; 69.1 kg in the elite teams and 63.5 kg in the collegiate team. In the collegiate team, the wide range in body mass meant that 26% of players were playing against teammates that were twice their weight, as were 24% of elite players. The range of heights in both collegiate and elite players was similar (28.5 cm and 30.0 cm respectively).

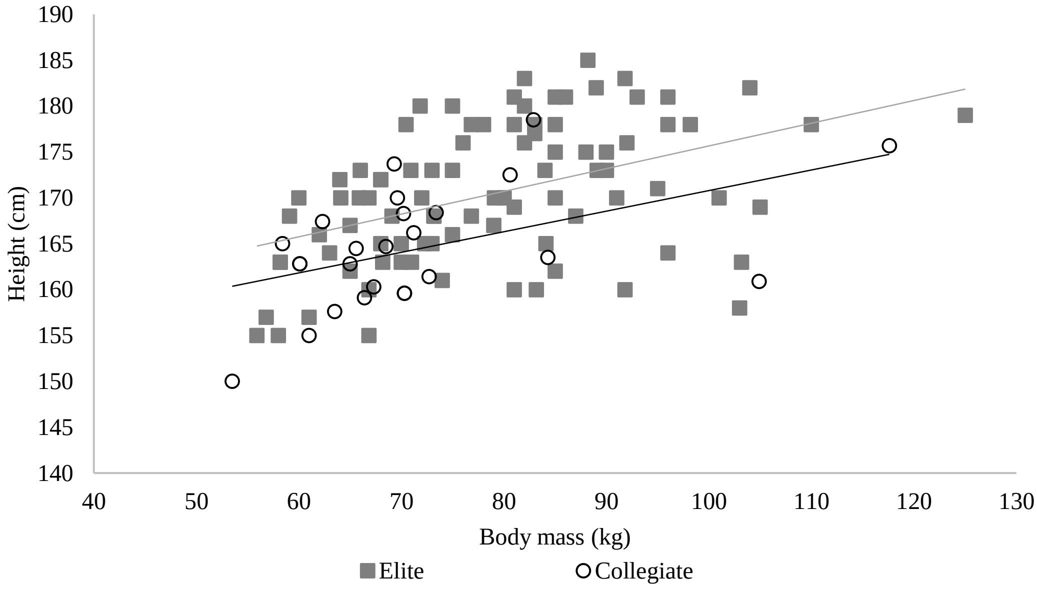


Figure 31: Scatterplot showing height and body mass of collegiate and elite players. The white points represent collegiate players, the dark grey represent elite players.

The elite players had been playing rugby for a significantly greater number of years (*p*<0.001) than the collegiate players and had a larger range in number of years playing rugby (20 years compared to 14). The elite players were on average six years older than collegiate. The majority of elite players had joined rugby in childhood: 47% below the age of 10 and 35.5% aged between 11 and 18 whereas a minority of collegiate players played rugby in childhood (29.4%).

Match Characteristics between Elite and Collegiate Cohorts

In the elite cohort, the median number of tackles per game was 168, whereas in the collegiate cohort, this number was 196. In both the collegiate and elite women's cohorts winning margins were significantly greater than those reported in respective male ($p<0.05$) competition. No significant difference was found between the winning margins of collegiate and elite women's matches (*p*=0.322), or between collegiate and elite men's matches (*p*=0.669, Figure 32). Substitute players were utilised slightly differently across cohorts: in the collegiate teams, players were replaced sporadically due to injury or around half-time, whereas elite players seemed to switch players in the closing 30 minutes of the game.

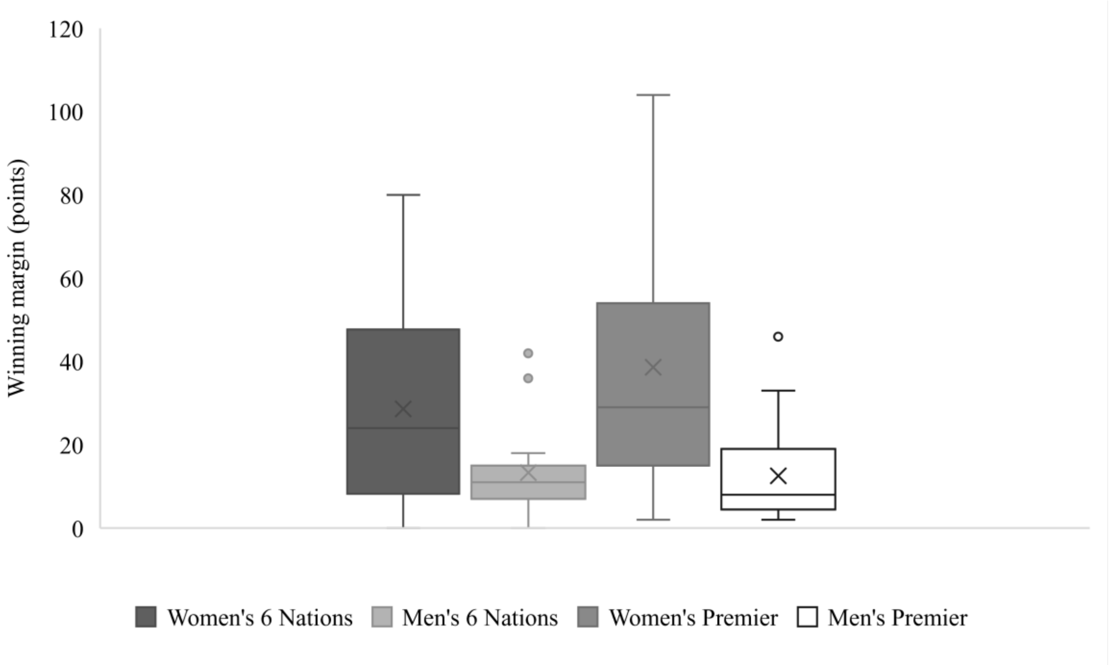


Figure 32: Winning margins between male and female, collegiate and elite teams.

Observed Head Acceleration Events Across Collegiate and Elite Players

Collegiate HAEs occurred at double the rate of elite HAEs: a collegiate HAE occurred every 48 seconds while an elite HAE occurred every 1 min and 36 seconds. In both collegiate and elite players, carriers experienced a greater proportion (57.4% collegiate, 56.3% elite) of HAEs than tacklers (42.6% collegiate, 43.7% elite). In the elite teams, a smaller proportion of tackles (14.6%) and carries (18.7%) resulted in a HAE compared to collegiate play (tackles 27.1%, carries 36.5%). In both playing levels, forward players performed tackles at a greater rate than backs: collegiate forwards performed 2.6 times, and elite forwards performed 1.7 times, more tackles than their respective backs. Collegiate forwards performed 2.5 times more carries than backs, whereas elite backs performed 2.4 times more carries than forwards.

Causes of Head Acceleration Events Compared Across Collegiate and Elite Players

The ball carrier was more likely to experience a head-to-ground impact (1.2 times in collegiate, 1.5 times in elite) than the tackler in both playing levels (Figure 33). A similar pattern was present in indirect HAEs; collegiate carriers were 2.4 times, and elite carriers 3.1 times, more likely to experience HAE caused by this mechanism. In collegiate and elite game player-to-player contact was the most common cause of HAE.

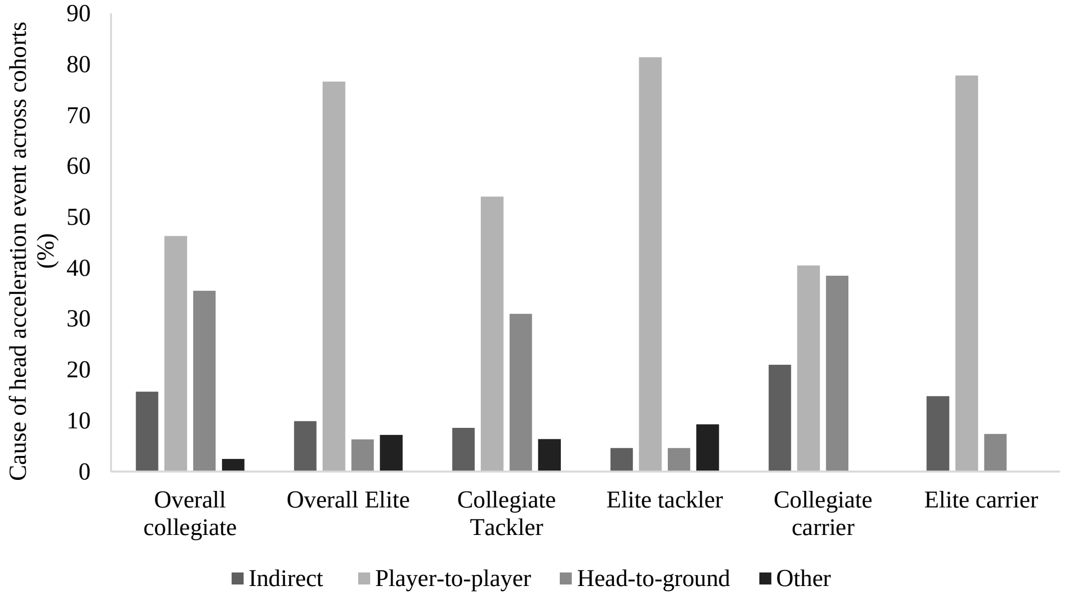


Figure 33: Causes of head acceleration events in collegiate and elite teams

The pattern of body parts contacted differed between collegiate and elite players (Figure 34). In collegiate players, 40.6% of player-to-player HAEs resulted from contact above the hip and 59.4% on or below the hip. In elite players, these proportions were inverted: 60.9% were the result of contact above the hip, with 39.1% below the hip.

Collegiate players were 7.5 times more likely to experience WSHK than elite players. In collegiate players, 70% of WSHK were observed in head-to-ground and 30% in indirect HAEs. In elite players, the majority of WSHK occurred indirectly (58.8%), with the remaining caused by head-to-ground contact (41.2%). In both playing levels the carrier was more likely to experience WSHK than the tackler (Figure 35).

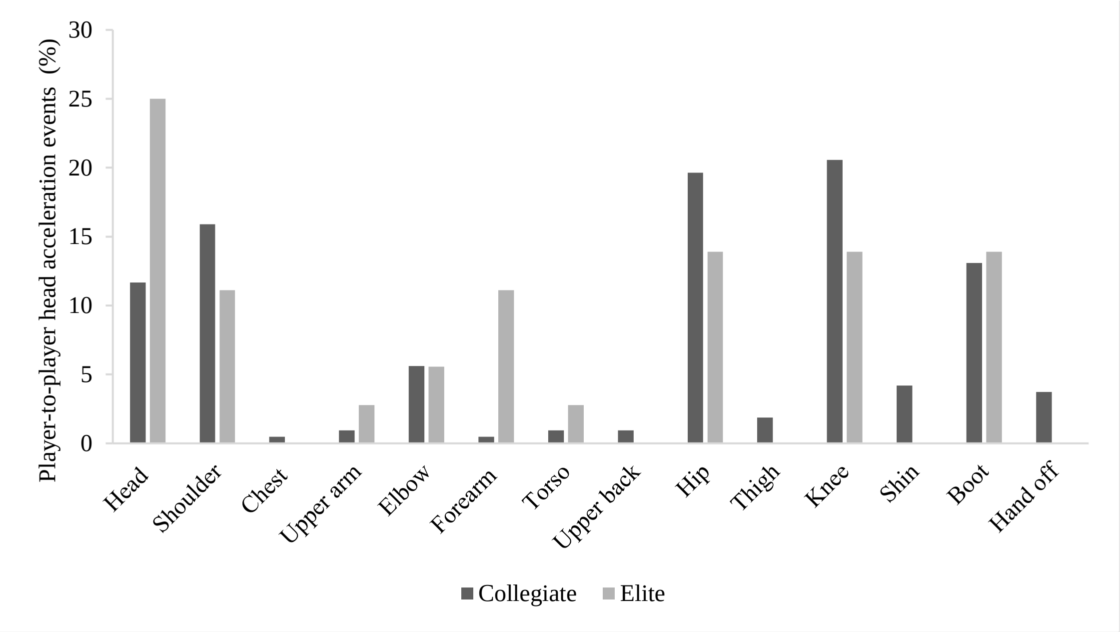


Figure 34: Body parts contacted with the head in player-to-player head acceleration events

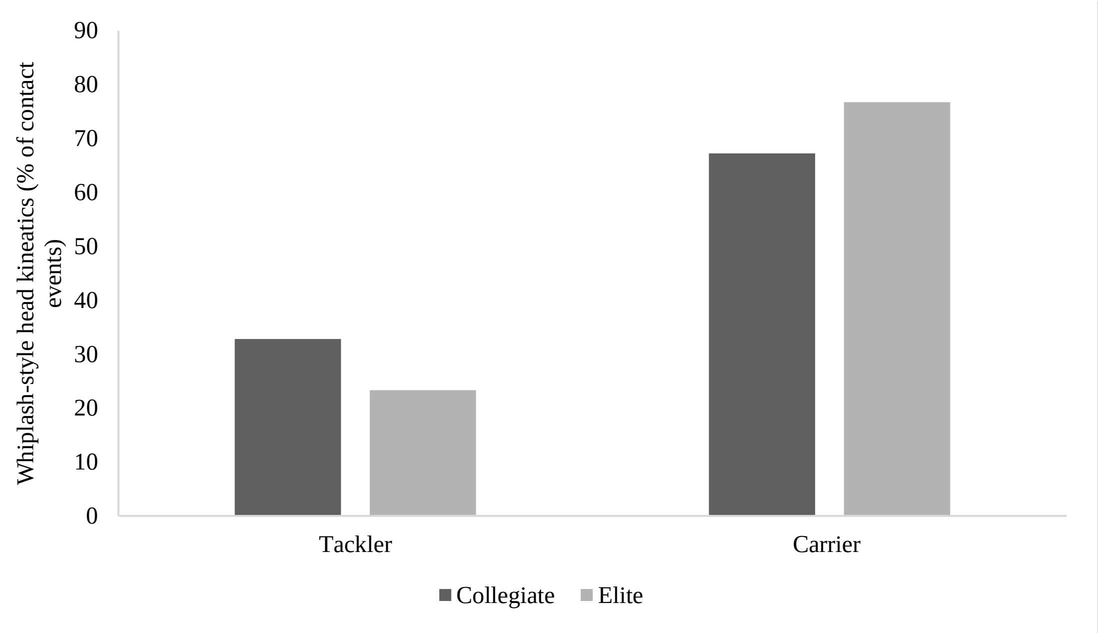


Figure 35: Percentage of total whiplash style head kinematics experienced by tacklers and carriers

Phase of Head Acceleration Events in Collegiate and Elite Players

In both collegiate and elite players, the proportions of HAEs that occurred in Phase 3 were similar (collegiate 15.1%, elite 14.2%). Elite players were 2.1 times more likely to experience a HAE in Phase 1 than the collegiate players, yet the elites were 1.7 times less likely to experience a HAE in Phase 2. In elite players, a greater proportion of Phase

1 player-to-player HAEs occurred via contact above the hip (61% collegiate, 96% elite). In elite players, no player-to-player HAEs resulted from contact above the hip, compared to 7% in collegiate players (Figure 36).

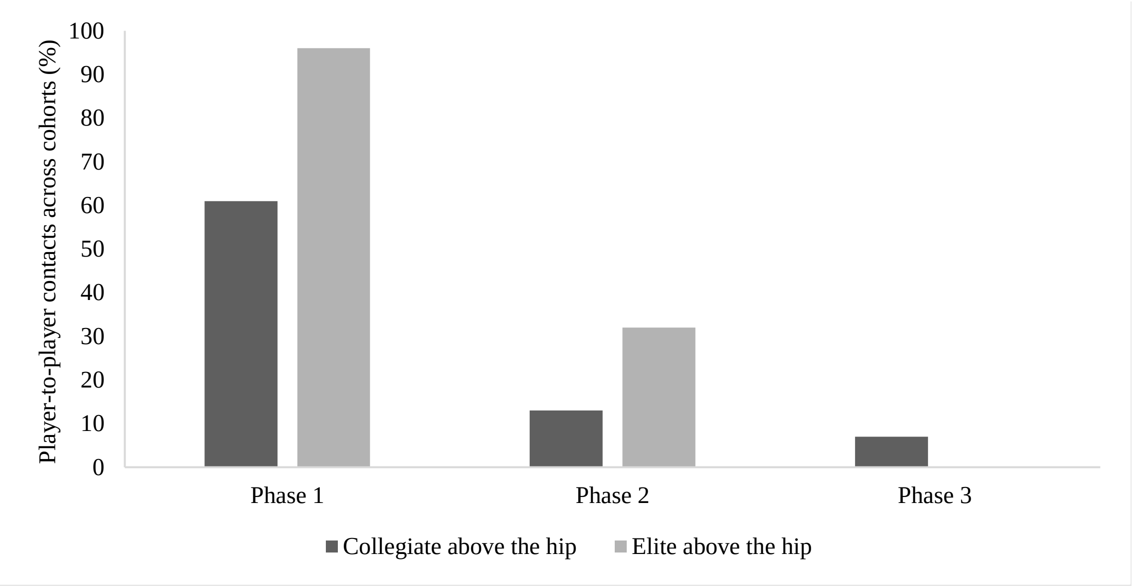


Figure 36: Percentage of player-to-player head acceleration events that resulted from contact above the hip

Variation of Head Acceleration Events Incidence Between Players

Number of tackles per match was slightly higher in collegiate game play than in elite (five tackles and carries in the collegiate team compared to three tackles and carries in the elite). The number of tackles performed by each player varied extensively, ranging from 0 to 10 in collegiate play and 1 to 20 in elite play. In both playing levels the variation in the number of carries was wide, ranging from 0 to 16 in collegiate teams and 0 to 13 in elite teams. No significant difference was found between the total number of contact events performed at each playing level (p=0.336). Collegiate players experienced significantly more HAEs than elites (p<0.01). Both collegiate and elite teams showed significant, positive correlation between the number of contact events performed and the number of HAEs experienced (collegiate 0.785, elite 0.504), (Figure 37).

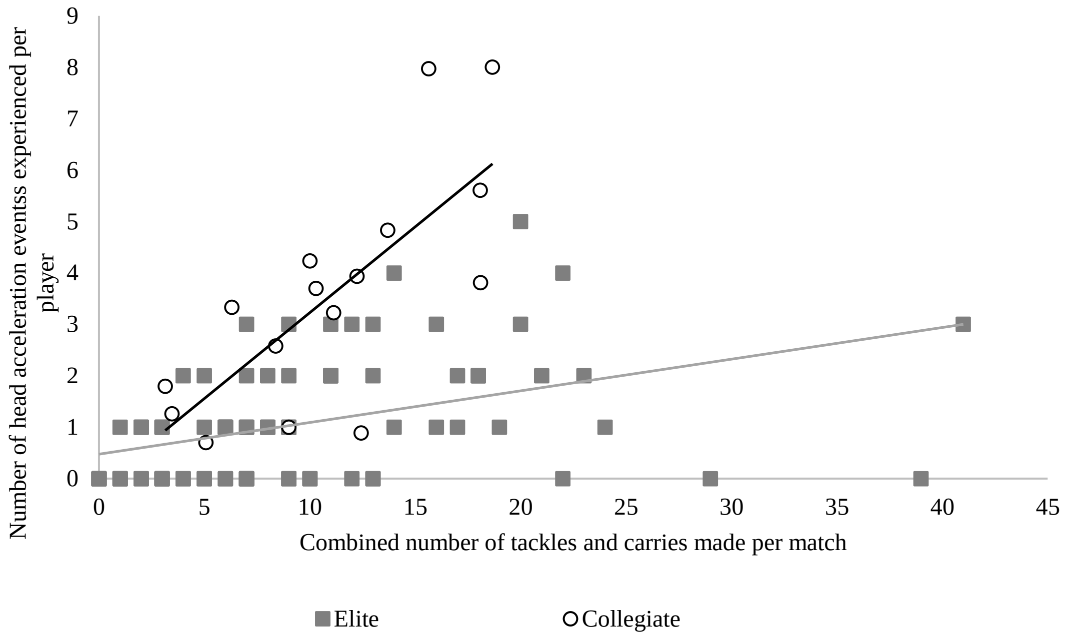


Figure 37: Scatterplot showing the number of head acceleration events and contact events performed by collegiate and elite players.

Chapter 5: Discussion

The aim of this study was to investigate head acceleration kinematics in female rugby players from collegiate and elite demographics. Head acceleration kinematics were found to differ between levels of play and from existing male derived literature. Within rugby union, current research is heavily focused on reducing concussion incidence and promoting long term brain health. Research effort is significant and evidence-based concussion management protocols are under continuous development. However, this evidence base rarely includes data from female players. When female data are used, elite players are generally the only demographic studied. Head acceleration kinematics from two playing levels were analysed to identify similarities and differences across playing levels.

5.1 Player Characteristics

Anthropometric differences between collegiate forward and backs were not significantly different. These findings were not consistent with elite male and female teams, where forwards were significantly heavier than backs (Gabbett, 2007; Lindsay, Draper, Lewis, Gieseg, & Gill, 2015a). The comparatively small collegiate training load and inconsistent playing positions may limit specialisation to forward or back play. Several players reported positional alterations across seasons and matches. Strength conditioning is limited in the university holidays, where lack of coach-led training and access to sports facilities may result in deconditioning. The rate of deconditioning in collegiate players is yet to be studied. Future study may benefit from regular anthropometric, fitness and strength testing to understand how these attributes change over on and off-season periods. These measurements may reveal how conditioning during the season and deconditioning post season varies between players. Although non-significant, differences between collegiate team forward and back anthropometrics are likely greater in this study than in a typical collegiate team. The collegiate team played at a relatively high collegiate level and several players were national representatives. The collegiate players in this study benefited from trainer-led strength training and from coach presence at matches. Where universities can't afford coaches and adequate training facilities, players may be required to coach themselves through potentially dangerous movement patterns.

Elite forward players were significantly taller and heavier than elite backs. This is consistent with previous studies in elite male and female athletes, where differences in weight are attributed to position-specific conditioning practices (Bradley, Board, Hogg, & Archer, 2020; Jones et al., 2016; Smith, 2017).

For both the collegiate cohort and data from elite players, the range in body mass between teams was wide: 25.0 - 27.7% of players weighed less than the range in body mass for their cohort, respectively. Players were therefore competing with and against players up to twice their body mass. In the male teams from the 2020 Six Nations, no player from the English, French and Welsh teams weighed less than the weight range (79 – 151 kg) (Six Nations Rugby, 2020; Six Nations Rugby, 2020b, 2020a, 2020c). As elite forwards complete most of the tackles and backs most of the carries (Jones et al., 2016), the lightest and heaviest players likely compete directly against each other. Other sports such as boxing have weight categories spanning just 3.3 kg, with the intentions of equalising size and strength between oppositions (Boxing GB, 2019). In rugby, it can be argued that certain positions are best played by lighter players. Concussion risk, however, may be elevated if there is a large body mass difference between players. Whilst England Rugby report that there is no evidence that weight banding would reduce injuries (England Rugby, 2012), several Scottish teams and New Zealand's Rugby Union have imposed weight cut-offs in age graded rugby to allow children equal playing opportunities (World Rugby, 2014). American football has also adopted weight banding in age graded play (Kerr et al., 2015). Whilst a large weight range between players may elevate injury risk, weight banding may not protect collegiate women. If fewer players are eligible to compete, teams may not have substitutes mid-game or may not be able to field a team at all. Whilst it is unlikely any weight banding will be introduced in adult women's rugby; lighter players may benefit from increased strength training to minimise these ranges.

Age, Playing Experience and Participation in Sports

Elite teams had a greater median age than the collegiate team and joined the sport at an earlier age. In the women's elite team, 70.6% of players had joined rugby in childhood (Six Nations Rugby, 2020a), whereas this was the case for only 17.6% of the collegiate women. In a parallel study, 92% of the collegiate male team had joined rugby in childhood. By participating in rugby early in life, players benefit from gradual conditioning and progress to contact over several years rather than being rushed to participate in matches.

In addition to joining rugby later than men, women are less physically active in childhood than boys. In 2018, 74% of primary school boys in Wales met physical activity guidelines compared to 60% of girls (Reyes et al., 2018; Sport Wales, 2013). In adolescence this gender gap widened, as almost double the percentage of boys adhered to guidelines compared to girls (Belton, O’Brien, Issartel, McGrane, & Powell, 2016). Limited physical activity may hinder the development of physical literacy, in turn elevating injury risk and decreasing motivation to participate in sports (Zwolski et al., 2017). Pre-puberty, boys have more developed fundamental movement skills, specifically in object control tasks (Bolger et al., 2018). Girls generally have lower fundamental movement skills, except for in locomotor skills. Several studies conclude that these differences do not result from genetics or biological sex differences, but rather from the types of sports boys and girls generally play (Bolger et al., 2018; Valentini et al., 2016).

Children commonly choose sports to participate in based on gender stereotypes (Cárcamo, Moreno, & del Barrio, 2020) and girls may be dissuaded from joining rugby, a typically male dominated sport. In the school sports survey, boys were more likely to participate in extracurricular contact sports (Sport Wales, 2013). Four contact sports were listed in the top ten boys’ sports: 37% of boys participated in football, 23% in rugby, 12% in martial arts and 11% in boxing. Only 13% of girls took part in football, the only contact sport listed in the top ten. The sports that boys choose to participate in may condition them to withstand the collisions seen in rugby. Football and rugby may prepare players to anticipate contact and martial arts develop fall technique and coordination (Gutierrez-Garcia, Astrain, Izquierdo, Gomez-Alonso, & Yague, 2018). England Boxing allows children older than ten to spar with children of a similar age. Although controversial, this ruling may begin to condition the neck to attenuate forces caused by indirect impacts (England Boxing, 2020).

In biographies of the WN2 team, players who joined the sport from a young age commonly had close family directly involved in the sport (Six Nations Rugby, 2020a). Several players also reported that girls were the minority in mixed-sex age grading.

Without this family tie there may be little to encourage participation in youth rugby, especially where there may be too few members to field a women's team once genders separate in adolescent rugby.

Early involvement within the sport gives players a wide skill base. This may be especially important in the women's game, where players frequently switch positions since numbers are limited. As is common in other sports, positional specialisation in rugby is not encouraged until the U13 level (England Rugby, 2012). Instead, coaches expose players to a variety of skills and positions with the aim of building a foundation before players specialise as forwards and backs. Frequent opportunities to practice tackling and a more gradual approach to contact may make safer technique more natural, protecting a player when contact is not anticipated. Players new to the sport in university may be taught full contact over a matter of weeks. When thrown into full contact, players tend to 'fall back on learned technique' rather than improving it (England Rugby, 2012).

Differing Playing Abilities Within the Team

In both the collegiate and elite player observations, the number of tackles were significantly, positively correlated with the number of HAEs experienced. The individual involvement in contact events, however, ranged considerably. Although participation in rucks was not accounted for, the disproportionate involvement in contact present at both playing levels may expose certain players to elevated injury risk. The disparity in game involvement may be a consequence of the varying ability or lack of confidence performing contact events. In the university setting, long holidays over summer and Christmas may further the gap in abilities: those who play in external teams continue play and maintain contact fitness, whereas those who cease play in holidays become deconditioned.

5.2 Match Characteristics

In both the collegiate and elite level, women's teams had significantly larger winning margins than matches of equivalent level males. This indicates that the level of play in women's rugby is wider ranging than in men's rugby, even within elite competition. At the elite level, this discrepancy may result from the different training and playing contracts available to female players from different teams. As men's rugby has been professionalised since 1985, male teams generally have more established funding, therefore are more likely to be awarded full time playing contracts than women (Cummins, Melinz, King, Sanctuary, & Murphy, 2020; Rayner, 2017). In January 2019, the England's women's rugby team were the first team in the world to receive full time playing contracts, over three decades after the men's team (Rayner, 2017). Other elite women's teams are still not full-time professional players and must hold down other jobs to maintain an income. These players are not limited by ability, but by the lack of full-time contracts offered by their clubs. Players offered only part-time contracts are disadvantaged when competing with those training full time.

Where matches have such large winning margins, viewer enjoyment may be lost, further limiting the media coverage of women in sport (Kian, Vincent, & Mondello, 2008). To counteract this, England's Rugby Football Union outlined a plan to promote women within the sport (England Rugby, 2017). This campaign aims to create a welcoming environment for women, give schoolgirls the opportunity to play in childhood and redefine rugby as a unisex sport. A diagram reproduced from the report (Figure 38) illustrates how increased visibility of elite play feeds back to elevate grassroots participation. By elevating numbers within the sport, teams of similar levels will be more readily available to play. This may reduce player attrition as enjoyment of the sport is maintained and travel commitment to matches is reduced.

.

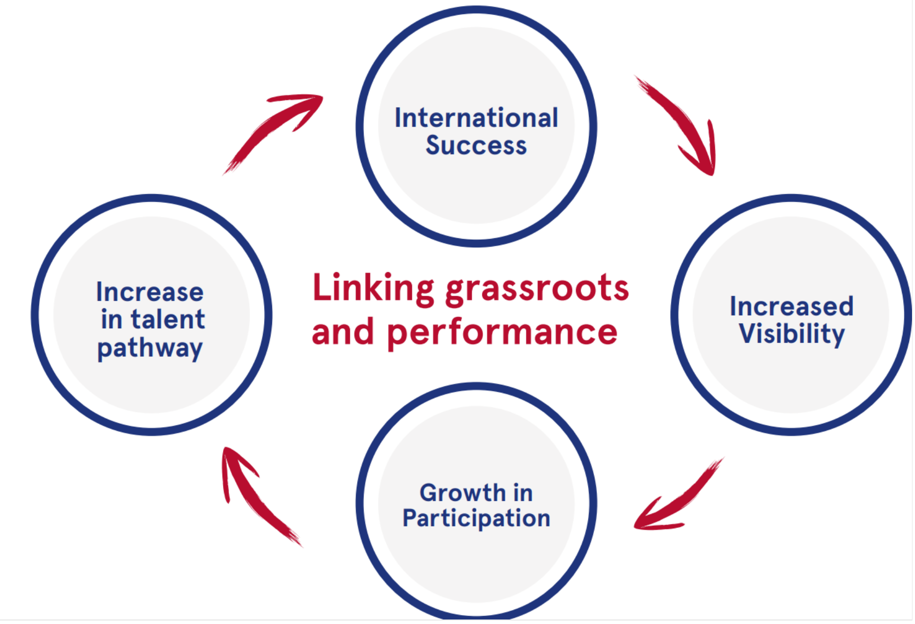


Figure 38: Diagram reproduced from the 'This is England Women's Rugby' Report

5.3 Description of Observed Head Acceleration Events

This study recorded 439 collegiate and 103 elite observed HAEs. Relevant literature often uses concussion incidence in kinematic research, however this study recorded HAEs in the absence of medical staff who could diagnose concussion. Identification of HAEs also acknowledged potential subconcussive impacts that may be more detrimental long term than a single concussion (Bailes, Petraglia, Omalu, Nauman, & Talavage, 2013; Mainwaring, Ferdinand Pennock, Mylabathula, & Alavie, 2018). Whilst concussion and HAE incidence are not directly comparable, it is likely that the two measures will be correlated.

Head Acceleration Event Incidence Between Collegiate and Elite Players

Collegiate HAEs occurred at double the rate observed in elite players. The number of contact events per collegiate and elite matches were similar, therefore contact exposure alone cannot account for this difference. The high HAE rates in collegiate play are likely a consequence of player inexperience or lack of conditioning.

Inexperience is significantly associated with injury risk in several sports (Anghelescu & Davila, 2019; Kamitani, Nimura, Nagahiro, Miyazaki, & Tomatsu, 2013; Pocecco et al., 2013; Sasaki et al., 2020) and may explain the results seen in the current study. In martial arts inexperienced judokas were reported to be less likely to demonstrate correct body positioning during contact. Consequently, poor fall technique was the predominant cause of concussion (Kamitani et al., 2013). In ice hockey, players less able to anticipate contact are more likely to be concussed (Mihalik et al., 2010). Inexperience within rugby may present as incorrect head positioning in contact, focus on the ball rather than upcoming collisions or poor fall technique post tackle. In the collegiate team studied, the more experienced players were generally less hesitant into contact and some more experienced players adopted rolling falls post contact. Hesitancy into contact allowed the opposition team to build line speed, elevating the force transfer between players. Additionally tackle proficiency was significantly decreased at faster line speeds as players were less able to make contact in the correct alignment (Gabbett & Kelly, 2007b).

The higher HAE incidence in novice players may result from greater acceleration and force production at tackle entry to compensate for less effective technique (Kerr et al., 2018). A previous study found that when players are shown an instructional video, experienced players are better able to apply learned content to practice (Kerr et al., 2018). This may be indicative of the tackle movement becoming more natural with practice (Kerr et al., 2018). In contrast, this finding indicates that a newer player may find the tackle movement complex and require extended practice in controlled settings before progressing to game play. Whilst the players in the collegiate team trained in small groups with highly qualified coaches, knowledge of correct technique may not translate to proficiency during actual contact (Van den Hollander, Lambert, Jones, & Hendricks, 2020). During matches, newer players have been reported to fall back on familiar movements rather than try newly learned contact techniques (England Rugby, 2012). Prolonged practice times before match involvement may therefore be key to promoting correct contact technique in newer players.

Poor rugby-specific conditioning may also contribute to the elevated HAE incidence in collegiate players. As playing level increases, strength and power of the players generally increase (Baker, 2002; Geeson-Brown, Jones, Till, Chantler, & Deighton, 2020). This greater strength reduces the risk of musculoskeletal injury and elevates the tolerance to external forces (Hislop et al., 2017). Relating this to concussion, stronger upper body musculature may attenuate forces during contact and reduce the acceleration of the head. Women generally have between 44 - 55% of the upper body strength of men (Augustsson et al., 2009), meaning the average female will be less able to withstand accelerative forces without injury. Women also had significantly weaker cervical musculature, having 68 ± 25% of flexion strength and 80 ±31% of the extension strength seen in height-matched males (Vasavada, Danaraj, & Siegmund, 2008). Despite the mitigation of concussion risk seen as strength increases (Collins et al., 2014), only 25% of women were reported to have taken part in resistance training twice per week (US Department of Health and Human Services, 2020).

Barriers to female participation in strength training were poor understanding of technique (Hurley et al., 2018) or intimidation by other gym goers (Salvatore & Marecek, 2010). To alleviate this, participation in strength training could be promoted though the publication of specific guidelines and incorporation into coach-led training sessions. As the collegiate team attended bi-weekly coach-led strength training, it is likely that these players were more conditioned than the general population of collegiate women’s rugby players. As a result, the incidence of HAEs in collegiate teams that do not have access to strength training may be greater than reported in this study.

At elite level, the top-two teams experienced the most HAEs. In higher ranked teams a smaller proportion of HAEs were caused by WSHK, therefore the increased incidence may result from player-to-player contact and increased physicality of the game. The WR4 team experienced the fewest HAEs, however, this team won their match by fifty points and were in attacking roles for the majority of the match. As only two matches were analysed, the disparity of HAE incidence across teams cannot be attributed to a particular cause. Further study may benefit from the analysis of a greater number of games from a wider range of teams across the world ranking to identify patterns in injury risk.

Reporting of Concussion Incidence

Concussion incidence could not be reported in this study, as no medical staff were present at matches able to diagnose concussions. During the matches recorded, several players demonstrated concussion symptoms, three of which were medically diagnosed, but outside of the university environment. The inability to diagnose concussion in collegiate and grassroots women's rugby may help to explain the lack of incidence reported in literature. In the handful of studies that have reported concussion rates, small sample sizes limit the generalisability of the results. The single elite women's injury surveillance report is compiled from a limited data set provided by six Premier 15 players over one season; the authors therefore conclude that results from the report should be interpreted 'cautiously' (Kemp, Fairweather, Williams, Stokes, West, Phillips, Byrne, et al., 2018). There is an urgent need for concussion incidence data across all demographics of women's rugby. The current absence of data prevents optimal injury management and limits the efficacy of targeted interventions.

No available literature reports the rate of concussion in collegiate women's rugby union. In elite women, concussion incidence ranges between 6.2 - 15 per 1000 playing hours (Kemp, Fairweather, Williams, Stokes, West, Phillips, Byrne, et al., 2018; King et al., 2019). This variability is thought to result from inconsistent applications of the HIA protocol rather than varying injury risk. Reports of concussion incidence in male players are also inconsistent. Some literature reports similar incidence across levels (13.3-17.9 per 1000 playing hours across community and elite players) (Brown et al., 2019; Kemp, Brown, et al., 2018; Kemp & Smith, 2019), whereas others report concussion incidence increasing as playing level increases (Bitchell et al., 2020b; Hancock et al., 2018). Growing evidence suggests that the female brain may be more vulnerable to accelerative forces, so that women may be at a greater risk of concussion from accelerations of a given magnitude (Antona-Makoshi et al., 2018; Broshek et al., 2005; Covassin, Moran, & Elbin, 2016; Dollé et al., 2018). This is not reflected in current rugby literature. The Women's Rugby Injury Surveillance Project state that 'Club medics do not see female players as regularly as in the men's premiership' therefore fewer injuries were detected (Kemp, Fairweather, Williams, Stokes, West, Phillips, Byrne, et al., 2018). Lack of access to club medics in the female game places women at a disadvantage in terms of their health and likely contributes to an underreporting of injury incidence.

Head Acceleration Event Incidence Between Tacklers and Carriers

In both collegiate and elite players, the ball carrier was exposed to more HAEs than the tackler. Across both collegiate and elite players, 56.3 – 57.4% of HAEs were experienced by the ball carrier. This is inconsistent with existing literature in elite male players, where 70% of concussions and 97% of head impacts were experienced by the tackler (Cross et al., 2019; Tierney et al., 2016). In collegiate male players the tackler/carrier HAE incidence was more equal, yet tacklers still experienced 56.7% of concussions (Suzuki et al., 2020a). The PLA and PRA of HAEs did not significantly differ between tacklers and carriers, however, the small sample size of this study may underpower the statistics.

Head Acceleration Event Incidence Between Forwards and Backs

In the collegiate team forwards completed double the tackles of the backs, but 2.4 times less carries. Playing data could only be disaggregated across playing position in one collegiate team, therefore further study is required before generalisations can be made to collegiate women's rugby. However, these results highlight the differing positional requirements present outside of forward specific events such as line outs. In the elite games, analysed forwards completed twice as many tackles and 2.8 times as many carries than backs, yet no significant difference was found between forward or back propensity to experience a HAE in either playing level. These results may be explained by the increased resilience of forward players and position specific conditioning undertaken in more elite teams. The results from this study are consistent with concussion reporting from the elite women's game, where concussion incidence between forwards and backs was not significantly different (Rugby Football Union, 2014). Findings from the elite female players were not consistent with the male elite game, where forwards performed significantly more tackles than backs, but backs performed the majority of carries (Lindsay, Draper, Lewis, Gieseg, & Gill, 2015b). The reasoning behind this inconsistency is not yet clear however, the team tactics utilised throughout the two matches may alter the proportion of contact experienced by forward and back players, especially in the match between the WN4 and WN9 teams where the WN4 players had disproportionate possession of the ball and won by fifty points.

Causes of Observed Head Acceleration Events

Player-to-player contact was the most common cause of HAE across both cohorts in this study. This finding is consistent with professional men's rugby (Tucker, Raftery, et al., 2017). The proportion of HAEs caused by indirect mechanisms was 2.4 and 3.1 times higher in collegiate and elite carriers respectively than tacklers. Tacklers may be at lower risk of experiencing indirect HAEs as their head can be supported against the carrier during contact. Particularly in an active shoulder tackle, the tackler holds their head tight against the carrier stabilising the upper body. The tackler is also able to anticipate contact, therefore proprioceptive action can be made to attenuate forces via muscle stabilisation.

Elite players experienced twice the head-to-head contact than the collegiate players, but less shoulder, hip and knee to head contacts. In 60.9% of elite player-to-player HAEs, contact was made between the head and body parts above the hip. In collegiate player-to-player HAE these proportions were reversed. These results may be explained by the increased intensity of support play from elite players. Elite players were faster to enter rucks and committed more players. This meant that players anticipating the ruck were often in very close proximity to the ball; as the carrier fell HAEs were commonly caused by their head contacting the players moving in to support the ruck. In elite men, the most common body part contacted was the head, as is consistent with the elite women in this study (Tucker, Hester, et al., 2017b). The body parts most frequently involved in contact after the head where the elbow, knee, hip and shoulder (Tucker, Hester, et al., 2017a), whereas in the elite women head contact was most prevalent followed by shoulder, boot and hip. In the collegiate women, head-to-head contact was the fifth most common cause of HAE, with contact between the knee, hip and shoulder being more prevalent. A similar study into men's elite play found that head-to-head, head-to-ground or head-to-knee had the highest propensity to cause concussion, but noted that contacts with these areas occurred relatively infrequently in comparison to trunk and lower limbs (Cross et al., 2019).

Head-to-Ground Head Acceleration Events

The proportion of head-to-ground HAEs was 5.6 times higher in collegiate players than elite players. These head-to-ground HAEs incorporated WSHK as players appeared to lose control of cervical musculature during their fall from contact. Conversely, certain players seemed able to stabilise their head as they fell, likely through the ability to activate the cervical spine musculature to prevent their head from contacting the ground (Collins et al., 2014; Salmon, 2014). Years of contact and strength training undertaken by elite players may increase cervical muscle strength even if the cervical musculature was not specifically targeted. The comparative cervical weakness in women may explain the high incidence of WSHK in female players and the general absence in male (Hrysomallis, 2016; Vasavada et al., 2008).

Poor falling skill may explain the high proportion of HAEs in the collegiate teams. Collegiate players often fell backwards in an uncontrolled fashion, experiencing HAEs from ground contact or incoming players. When people join rugby as adults, they are generally taught to fall within one training session. These falling drills often focus on the role of the carrier and cannot represent the intensity expected in matches. As previously mentioned, newer players tend to 'fall back on learned technique rather than practicing new skills' during match play (England Rugby, 2012). Players may therefore benefit from repeated fall drills, especially after breaks in play such as university holidays.

In comparison, the elite players seemed to actively control their fall by twisting mid-air to land on their front or putting an arm down to break their fall. Carriers were then better able to avoid contact from incoming players and present the ball to advantage their team.

Whiplash Style Head Kinematics

This study reported head acceleration kinematics not previously documented within rugby. WSHK were present in a considerable proportion of collegiate and elite HAEs (51.2% and 16.2% respectively) yet had not previously been acknowledged in concussion research. In the men's game, most concussions occur exclusively through player-to-player contact (Burger et al., 2015; Hendricks et al., 2016) with WSHK only present if the player loses consciousness before the fall. The failure to research concussion mechanisms in both sexes presents a large gender data gap in rugby.

In the collegiate cohort, the median PLA and PRA for WSHKs were 12 g (IQR 6.5 g) and 843 rad/s^2 (IQR 763 rad/s^2), respectively and were present in 13.8% of tackles and 17.7% of carries. These values were not significantly different to other causes of HAE, although significance may become apparent within a larger data set. WSHK appeared to vary considerably across players; certain individuals experienced WSHK with almost every contact event whereas others appeared more able to withstand the accelerative forces. WHSK were present in even the most experienced collegiate players, indicating that neck strength and the ability to activate these muscles is not naturally adaptive. Rather, it must be specifically trained.

Whiplash injury resulting from vehicle collision may result in balance deficits, proprioceptive disturbance and reduced cervical range of motion (Fernández-Pérez et al., 2012; McPherson, Nagai, Webster, & Hewett, 2019). As female players were frequently exposed to WSHK, low level damage to cervical musculature may accumulate over the season. The resultant deficits may elevate concussion risk as players are less able to anticipate contact following the reduction of cervical range of motion (Fernández-Pérez et al., 2012). Additionally, the fatigue and strain to cervical musculature post-match, may further reduce the attenuation of force transmission through the neck. As these deficits may remain beyond three months post-injury (Sterling, Jull, Vicenzino, Kenardy, & Darnell, 2003), subtle symptomology may not be recovered in the off season, leaving players vulnerable to further injury in subsequent seasons.

At the start of the playing season, 58.8% of the collegiate cohort reported that they had been concussed (35.3% multiple times). With consideration of this, in addition to them experiencing repetitive WSHK, sensory and motor deficits may already be present despite their short playing careers. As sub-clinical abnormalities can remain beyond the recommendations of return to play protocols, non-recovered neuronal damage may accumulate over a playing career (Buckley, 2014; Mainwaring et al., 2018). Gait and postural control alterations were detectable one month post-concussion, which means that players may be less able to perform safe contact technique (Buckley, 2014; Howell, Osternig, Koester, & Chou, 2014). Sleep disturbances are detectable three months post-concussion and electroencephalographic abnormalities remain present for up to a year (Jaffee, Winter, Jones, & Ling, 2015; Slobounov et al., 2017; Slobounov, Sebastianelli, & Hallett, 2012). As our understanding of subconcussive accelerations and their effect on brain health improves, it is increasingly clear that female-specific research in rugby is needed if we are to protect women from avoidable injury.

Additionally, further study of WSHK in sporting contexts is highly relevant to vehicle collision research. As HAE or WHSK cannot be experimentally induced, studies are generally unable to quantify accelerations in a non-sporting population. Both areas of study may benefit from this collaboration – whiplash research may inform recovery protocols and SRC research may aid the understanding of injury mechanisms.

Phase of Contact

HAE magnitudes across contact phases were not significantly different between cohorts, however, incidence across phases did differ. Collegiate players experienced 56.2% of HAEs in Phase 2, whereas elite players experienced 52.6% of HAEs in Phase 1. The proportional differences across cohorts may be explained by elite players generally entering contact at greater speeds and collegiate players being particularly vulnerable to head-to-ground accelerations. While certain collegiate players tended to hesitate into contact, elite players accelerated towards the tackles and generally committed more people. As such, energy transfer appeared to be greatest in Phase 1 of elite contact and players were in closer proximity to each other.

Player-to-player contact was least common in Phase 3, causing less than 16% of HAEs in each cohort. Phase 3 HAEs mostly resulted from accidental contact between the carrier's head and the lower limbs of rucking players as they step over the ball. HAE incidence within rucking players is not commonly studied as head movement is difficult to identify on video. Front-on collisions and high player density in the ruck, however, may expose players to a high number of HAEs. Research from literature does not comment on HAEs occurring in Phase 3 (Burger et al., 2015; Read et al., 2017; Suzuki et al., 2020b), perhaps because only diagnosed concussions are reported, rather than lower magnitude HAEs. Male carriers may also be at less risk of Phase 3 HAEs, since their longer limb and stride length may facilitate greater clearance of the ball carrier as rucking players step over. In male players, concussions occurred almost exclusively in Phase 1 (Burger et al., 2015; Hendricks et al., 2016) and studies did not comment on the falling technique of players (Davidow et al., 2018; Hendricks et al., 2020; Suzuki et al., 2020b).

Variation of Incidence Between Players

In this study, the contact load was normalised to estimate volume per match. The number of contact events varied considerably in both cohorts and positively correlated with the number of HAEs experienced. This variation may be indicative of the reliance on more experienced players to make bigger tackles, particularly in collegiate teams. In a larger sample, a correlation between years of experience and HAEs-per-contact ratio may become apparent, as technique is less established in newer players (England Rugby, 2012; Kerr et al., 2018). Conversely, the variation in contact load was similar between elite and collegiate players. Elite players rarely hesitated into contact; therefore, players may have differing roles on the pitch. This study only accounted for tackles, so the players who performed fewer tackles may instead be disproportionately involved in rucks or running lines instead.

5.4 Quantified Head Acceleration Events

This study quantified 73 HAEs that passed strict video and waveform verification. The head impact telemetry systems are relatively new technologies, so current recording procedures are not yet standardised across studies. Different research groups often use custom filters and proprietary algorithms for the post-processing of data, which makes comparisons between studies difficult. In this study, every effort was made to ensure false positives were omitted from the data set. Whilst some true positives may have been missed, earlier research in this field tended to over report false impacts (Schnebel et al., 2007). The researcher therefore decided to prioritise validity over sample size to avoid reporting poor-quality data.

Median HAE magnitudes from this study were below those reported at all levels of rugby league using instrumented head patches: 16 g and 2773 rad/s^2 in junior rugby (King, Hume, Gissane, & Clark, 2017), 14g and 3181 rad/s^2 in amateur male rugby (King, Hume, Gissane, & Clark, 2017) and 15 g and 2886 rad/s^2 amateur female rugby (King et al., 2018). Although this study cannot report concussion incidence, obvious symptomology was present in the three impacts above 37 g. Conversely, values recorded by instrumented headbands have quantified diagnosed concussions at 18.6 g (Langevin et al., 2020). As headband-mounted systems generally overestimate magnitudes (Wu et al., 2016), this result implies that certain players may have considerably lower tolerance levels than others. The context of the concussion was not reported; however, this player may have been recently concussed or experienced several HAEs before concussion symptoms began to present. To determine which HAEs may be injurious, HAE density and match exposure should be investigated further.

Several studies have aimed to quantify head acceleration events in women, but to our knowledge only one published paper focuses on women's rugby union (Langevin et al., 2020). That study used instrumented headbands during training and matches and recorded median PLA values of 32.16g, over double that recorded in the current study. The values reported in Langevin et al are likely elevated by soft tissue artefact from scalp movement under the headbands (De Rosario, Page, Besa, Mata, & Conejero, 2012). Although the authors state that the sensors used are accurate (Langevin et al., 2020), the headbands record significantly different PLAs compared to a calibrated Hybrid III Headform and known pendulum swing values (Oeurl, & Blaine 2016). The accuracy testing revealed significant differences in PLA between the head form and headband; this tendency to overestimate impacts even in a highly controlled setting limits the accuracy of subsequent data sets. Moreover, the accuracy testing did not consider how scalp artefact and movement of (often long) hair in female players would elevate values, which likely contributes to the differing magnitudes across studies.

In rugby league two studies used instrumented patches to quantify head accelerations in the women's game and compare results with the men's game (King et al., 2019; King et al., 2018). Significantly higher median PLA were reported for male players than female (15.4 g in women, 14.6 g in men) but significantly lower PRA (2802.3 rad/s^2 in women, 2886.3 rad/s^2 in men). These values are slightly higher than reported in the current study, however the patch system has been found to overpredict PLA by 120% and PRA by 290% for (Wu et al., 2016). As a consequence, Wu et al., (2016) state 'the raw data from these sensors likely cannot be directly used to predict or study injury risks'. Although waveforms were filtered in this study, this post-processing cannot correct confounded acceleration values. When our unfiltered mean values were compared with those presented by King et al., (2015), impact magnitudes were closer together. The average unfiltered PLA was 17.3 ± 8.7 g. This decreased by an average of 20% after the data was low-pass filtered to remove high frequency noise. The average unfiltered PRA was 1316.1 ± 954.8 rad/s^2 and which decreased by an average of 21% after the low-pass filter was applied. Due to the methodological differences that currently exist between head impact studies, it remains difficult to evaluate the influence of sex differences on impact magnitude. Even where men and women are compared in the same study, poorly coupled sensors provide imprecise data. This is particularly problematic when used with long hair, which may exaggerate the movement of the sensor relative to the skull.

5.5 Potential Brain Injury Mitigation Strategies

This study has identified several areas of concern for female rugby players. Minimising exposure to avoidable HAEs will allow women to enjoy the many benefits to mental physical and social health associated with rugby.

Neck Strengthening Interventions

It is likely that inadequate neck strength and an inability to appropriately activate neck musculature contributes to the incidence of WSHK in women's rugby. Therefore, developing this musculature may have protective effects in minimising concussion risk. Existing literature provides support for this approach. Neck strengthening interventions have been found to successfully reduce the acceleration of the head (Benson et al., 2013; Streifer et al., 2019). For every 0.45 kg of neck strength, a corresponding 5% reduction in concussion risk has been reported (Collins et al., 2014). This strengthening should be particularly encouraged in women as sex differences within the cervical spine mean that women require greater relative strength to achieve equal force attenuation to men (Stemper et al., 2008; Vasavada et al., 2008). Despite the collegiate team completing neck strength exercises twice a week, incidence of WHSK experienced by these players remained high. At the beginning of the study, several players in the collegiate cohort did not have sufficient isometric neck strength to hold their head off the floor for ten seconds whilst in a supine position. However, this suggests that even with upper body training beyond that seen in a typical women's team, the neck is an area of significant weakness.

Players in this study reported anecdotally that a lack of awareness of the benefits and perceived silliness of the exercises were barriers to neck strength training. Many of the exercises involved a chin tuck to isolate the muscles of the neck. Given limited training times, players and coaches may be dissuaded from incorporating neck strength training due to the time spent isolating such a small muscle group. The development of neck strength exercises that can be used in conjunction with more compound movements may aid training efficiency and intervention adherence. For example, an isometric head lift could be held during lower abdominal exercises or hip-bridges.

Outside of coach-led strength training, several players admitted to feeling silly performing the exercises and would not feel comfortable performing them in a gym. Promotion of these exercises by elite players may encourage those at collegiate levels to continue neck strength training. Rugby Unions currently do not actively promote strength training as an injury protection strategy. The general public may not be aware of the value of this training, therefore may benefit from published guidelines of rugby specific exercises. The guidelines should prioritise safety and inexpensive equipment and should explain exercise progressions to allow matching to player ability.

For coaches, studying the falling technique of individual players in depth may not be practical or possible. However, it may be beneficial to analyse the video of one match per season to assess instances of WSHK in individual players. This would allow those most at risk to be identified and appropriate support and remediation training could then be implemented. Additionally, completing a self-reported neck pain scale post-match may also identify players exposed to injurious acceleration and allow assessment of recovery throughout the season. Academic investigation of the relative strength required to prevent WSHK would provide a threshold that players can train towards. This could be achieved via the neck strength testing of a large population of players, with corresponding video analysis of WSHK incidence.

Player Experience and Opportunity

At the current time, opportunities to play rugby are not equal between sexes. Whilst players can join mixed teams up to age eleven, fewer clubs have women’s senior teams. Consequently, teenage girls may be forced out of the sport. Although the low player numbers likely contribute to the lack of women’s age graded teams, promotion of the women’s game by WR could elevate uptake of the sport. There is also movement away from the male-dominant, male stereotype of clubs as many teams aim to make training facilities welcoming environments for female players (Cárcamo et al., 2020; England Rugby, 2017).

Integration of Players in the Collegiate Setting

Collegiate sport attracts many new players to women’s rugby. However, the BUCS competition takes full advantage of season lengths and match play may restart as early as October 9th. Due to smaller player numbers, new players may participate in their first match just two or three weeks after being introduced to the sport. Many coaches teach contact in a graduated fashion (albeit rushed in comparison to youth rugby), however these drills are often not repeated through the season. Several studies highlight the time required to consolidate new skills, like tackling, before they can be performed correctly and automatically (England Rugby, 2012; Kerr et al., 2018).

To ensure a minimum level of proficiency in players, governing bodies could implement a skills passport for new players. Players may be required to practically demonstrate correct contact technique and complete a simple online test. The online component could evaluate their understanding of legal play and basic concussion knowledge. This approach may facilitate knowledge transfer between researchers and coaches and ensures players have the right grounding before joining matches. A similar method is already used in sports such as CrossFit™'s OnRamp program (Inside the Affiliate, 2014). Participant safety is maintained as coaches prioritise correct technique and beginners are not immediately exposed to the exercise intensity of more senior members.

Learn to Fall Interventions

As the majority of collegiate HAE occurred during Phase 2, development of safer fall technique may significantly decrease exposure. Research from non-athletic populations conclude that women experience 33% more fall-related head and neck injuries than men and are particularly vulnerable to cervical fractures (Stevens & Sogolow, 2005).

In rugby, new players are generally taught to fall on their front or side and are discouraged from putting an arm out to catch themselves (World Rugby, 2020a). Fall drills are generally completed in one session. Whilst falling technique can be developed in as little as 15 minutes, these newly learned skills are not retained beyond 3 weeks (Sran, Stotz, Normandin, & Robinovitch, 2010). In men's rugby, players typically have good neck strength and avoid shoulder and wrist injuries by keeping their arms tucked in as they fall. Collegiate women in this study did not appear to have the neck strength to prevent their head contacting the floor so they may benefit from female-specific falling drills that use arm positioning to reduce head contact. Neck strength training should not be abandoned; rather an altered fall strategy may protect players as neck strength develops.

Insight from fall mitigation strategies in older adults could be adapted to better protect rugby players. Tuck and roll falls were the most effective fall strategy for reducing impact severity (DeGoede et al., 2003). Further research must consider the likelihood of Phase 3 impacts as the ball carrier rolls into rucking players. Drills preparing players to fall from all directions should also be incorporated. Front-on tackles often cause players to fall backwards, however practice of this movement may be too dangerous to practice on the field. The adaptation of drills from child playground safety interventions (Toronjo-Hornillo, DelCastillo-Andrés, Campos-Mesa, Díaz Bernier, & Zagalaz Sánchez, 2018) may allow players to practice fall technique, but at gradual intensities to avoid injury. To ensure players are able to fall safely even from unanticipated contact, these fall techniques should be regularly practiced until the movement patterns can be performed automatically.

5.6 Study Limitations

The intention for this study was to video record at least ten collegiate matches, with corresponding real-time accelerometer data collected from players fitted with bespoke mouthguards. Due to the COVID19 pandemic, the 2019-2020 rugby union season ended prematurely. Had the number of players and matches been larger, the greater statistical power may have highlighted significant differences in head impact magnitude across causes and phases of HAE.

Challenges relating to the development of the iMG system also contributed to the reduced number of matches recorded. To mitigate this, the head acceleration kinematics of players not fitted with iMGs were included in the video analysis for observed HAE. HAEs were recorded by one researcher blinded to data from instrumented mouthguards. Testing of interrater reliability was not practical in this setting. However, incidence of HAEs is likely underreported, as tackling players were sometimes obscured in the video footage by teammates and less obvious head accelerations may not have been identified.

Only one team was fitted with iMGs, therefore the relationship between carrier on tackler HAE and could not be investigated. Several studies have reported an interaction between tackler, carrier and concussion risk (Stokes et al., 2019; Suzuki et al., 2020b; Tucker, Hester, et al., 2017a). A trial that reduced the legal tackle height decreased carrier concussion risk (Stokes et al., 2019). Consequently, it is necessary to understand the relative risk and accelerative load in both players to ensure that interventions do not cause unforeseen harm.

5.7 Future Directions

This study has identified mechanisms of HAE within collegiate women's rugby. This research should be replicated across a range of demographics to identify areas of improvement. Since WSKH may be related to poor cervical muscle strength, interventions that target this weakness may benefit players. These interventions should be promoted to players and effort should be made to facilitate their completion. Common place testing of neck strength, in elite and amateur players would allow the development of a data base of average neck strength across players. Furthermore, relating HAE incidence to neck strength may demonstrate a threshold of relative strength at which players experience rarely WSHK.

The discovery of female WSHK in rugby may also have relevance to fall-related injury in other sports and more general populations. Demographics where neck and upper body muscle strength is limited may be particularly vulnerable to similar injuries. This finding may warrant further screening in at-risk populations such as older adults. Demographic-specific neck strength training protocols may be developed.

Research teams quantifying head accelerations should work towards a standardised recording methodology, verification and filtering protocols to improve accuracy and comparability across studies. Quantification of HAEs coupled with greater contextual data and neurocognitive testing would allow injury mechanisms to be better understood, particularly with larger sample sizes and longitudinal study.

5.8 Conclusions

This study has uncovered head acceleration kinematics in women's rugby that were previously undocumented in men's rugby. Further study is needed to better understand the implications of these data. The results from this study highlight the limited generalisability of androcentric injury protocols and concussion interventions. There is an urgent need to develop female specific concussion interventions, to prevent a future epidemic of neurodegenerative disease. Retired male American football and rugby players are now being diagnosed with dementia, motor neurone and Parkinson's disease. Women’s rugby union was professionalised three decades after the men’s, game. Thus, there may be a unique window of opportunity to intervene and prioritise the brain health of female players before this epidemic of neurodegeneration is repeated in women.

For this to be achieved, rugby unions must understand how current training recommendations and injury management protocols developed from androcentric data have limited generalisability to female players. Sports science research as a whole should prioritise greater sex-disaggregation of data and equal focus on both males and females. By actively working towards closure of the gender data gap, women will not be disadvantaged in healthcare or sporting contexts.

References

Alamgir Khan, & Sultan Jalal-ud-din Faisal. (2018). CT Scan Findings in Mild Traumatic Head Injury in Adults. *Journal of Rawalpindi Medical College (JRMC)*, *22*(4), 322–326.

Alosco, M. L., Mez, J., Tripodis, Y., Kiernan, P. T., Abdolmohammadi, B., Murphy, L., … McKee, A. C. (2018). Age of first exposure to tackle football and chronic traumatic encephalopathy. *Annals of Neurology*, *83*(5), 886–901. Retrieved from http://doi.wiley.com/10.1002/ana.25245

Altunsöz, I. H., & Goodway, J. D. (2016). SKIPing to motor competence: the influence of project successful kinesthetic instruction for preschoolers on motor competence of disadvantaged preschoolers. *Physical Education and Sport Pedagogy*, *21*(4), 366–385. Retrieved from https://www.tandfonline.com/doi/abs/10.1080/17408989.2015.1017453

Anghelescu, A., & Davila, C. (2019). Short narrative review on main winter sports-related accidents: epidemiology, injury patterns, arguments for prophylactic behavior to avoid orthopedic and catastrophic neurological injuries. *Balneo Research Journal* . Retrieved from https://pdfs.semanticscholar.org/d1e3/83b43c93248e0e4224e1e7985acafe5576cc.pdf

Antona-Makoshi, J., Mikami, K., Lindkvist, M., Davidsson, J., & Schick, S. (2018). Accident analysis to support the development of strategies for the prevention of brain injuries in car crashes. *Accident Analysis and Prevention*, *117*, 98–105.

Arto On', C., Oeurl, R. A., & Blaine ~oshizaki', T. (2016). MEASUREMENT ACCURACY OF HEAD IMPACT MONITORING SENSOR IN SPORT. In *ISBS - Conference Proceedings Archive*. Retrieved from https://ojs.ub.uni-konstanz.de/cpa/article/view/6994

Augustsson, S. R., Bersås, E., Thomas, E. M., Sahlberg, M., Augustsson, J., & Svantesson, U. (2009). Gender differences and reliability of selected physical performance tests in young women and men. *Advances in Physiotherapy*, *11*(2), 64–70. Retrieved from http://www.tandfonline.com/doi/full/10.1080/14038190801999679

Axen, K., Haas, F., Schicchi, J., & Merrick, J. (1992). Progressive resistance neck exercises using a compressible ball coupled with an air pressure gauge. *Journal of Orthopaedic and Sports Physical Therapy*, *16*(6), 275–280. Retrieved from www.jospt.org

Bailes, J. E., Petraglia, A. L., Omalu, B. I., Nauman, E., & Talavage, T. (2013). Role of subconcussion in repetitive mild traumatic brain injury. *Journal of Neurosurgery*, *119*(5), 1235–1245. Retrieved from http://thejns.org/doi/abs/10.3171/2013.7.JNS121822

Bailes, J., Petraglia, A. L., Omalu, B. I., Nauman, E., & Talavage, T. M. (2013). Role of subconcussion in repetitive mild traumatic brain injury. *Journal of Neurosurgery*, *119*(5). Retrieved from https://thejns.org/view/journals/j-neurosurg/119/5/article-p1235.xml

Bailey, S., Martindale, R., Sweeting, J., Deacon, J., Laing, F., Leck, C., & Palmer, D. (2020). Effects of a strength and proprioceptive training programme on neck function and concussion injury risk in elite scottish rugby union players - ProQuest. *Br J Sports Med*, *54*(1). Retrieved from https://search.proquest.com/docview/2370281412?pq-origsite=gscholar&fromopenview=true

Baker, D. (2002). Differences in Strength and Power Among JuniorHigh, Senior-High, College-Aged, and Elite Professional Rugby League Players. *Journal of Strength and Conditioning Research*, 581–585.

Barnett, L. M., Stodden, D., Cohen, K. E., Smith, J. J., Lubans, D. R., Lenoir, M., … Morgan, P. J. (2016). Fundamental movement skills: An important focus. *Journal of Teaching in Physical Education*, *35*(3), 219–225. Retrieved from https://journals.humankinetics.com/view/journals/jtpe/35/3/article-p219.xml

Barnett, L. M., van Beurden, E., Morgan, P. J., Brooks, L. O., & Beard, J. R. (2009). Childhood Motor Skill Proficiency as a Predictor of Adolescent Physical Activity. *Journal of Adolescent Health*, *44*(3), 252–259.

Bartsch, A., Samorezov, S., Benzel, E., Miele, V., & Brett, D. (2014). Validation of an “intelligent Mouthguard” Single Event Head Impact Dosimeter. *SAE Technical Papers*, *2014-November*(November). Retrieved from https://www.sae.org/publications/technical-papers/content/2014-22-0001/

Beattie, J., & Magee, S. (2008, September). BBC Panorama - Rugby and the Brain: Tackling the truth. In *Archives of Clinical Neuropsychology*. Retrieved from https://academic.oup.com/acn/article-lookup/doi/10.1016/j.acn.2008.05.002

Belton, S., O’Brien, W., Issartel, J., McGrane, B., & Powell, D. (2016). Where does the time go? Patterns of physical activity in adolescent youth. *Journal of Science and Medicine in Sport*, *19*(11), 921–925.

Benson, B. W., McIntosh, A. S., Maddocks, D., Herring, S. A., Raftery, M., & Dvořák, J. (2013, April 1). What are the most effective risk-reduction strategies in sport concussion? *British Journal of Sports Medicine*, Vol. 47, pp. 321–326. Retrieved from http://bjsm.bmj.com/

Beyer, C. A., & Johnson, M. A. (2020). *REBOA in Traumatic Brain Injuries*. Springer, Cham.

Bieniek, K. F., Blessing, M. M., Heckman, M. G., Diehl, N. N., Serie, A. M., Paolini, M. A., … Dickson, D. W. (2020). Association between contact sports participation and chronic traumatic encephalopathy: a retrospective cohort study. *Brain Pathology*, *30*(1), 63–74. Retrieved from https://onlinelibrary.wiley.com/doi/abs/10.1111/bpa.12757

Bitchell, C. L., Mathema, P., & Moore, I. S. (2020a). Four-year match injury surveillance in male Welsh professional Rugby Union teams. *Physical Therapy in Sport*, *42*, 26–32.

Bitchell, C. L., Mathema, P., & Moore, I. S. (2020b). Four-year match injury surveillance in male Welsh professional Rugby Union teams. *Physical Therapy in Sport*, *42*, 26–32.

Black, S. E., Follmer, B., Mezzarane, R. A., Pearcey, G. E. P., Sun, Y., & Zehr, E. P. (2020). Exposure to impacts across a competitive rugby season impairs balance and neuromuscular function in female rugby athletes. *BMJ Open Sport & Exercise Medicine*, *6*(1), e000740. Retrieved from http://dx.doi.org/10.1136/bmjsem-2020-000740

Blitz defence. (2018). The Game's Gone Soft? A List of Rugby Players Forced to Retire Due to Brain Injuries | theblitzdefence. Retrieved August 24, 2020, from https://theblitzdefence.wordpress.com/2018/05/01/the-games-gone-soft-a-list-of-rugby-players-forced-to-retire-due-to-brain-injuries/

Bolger, L. E., Bolger, L. A., Neill, C. O., Coughlan, E., O'Brien, W., Lacey, S., & Burns, C. (2018). Age and sex differences in fundamental movement skills among a cohort of Irish school children. *Journal of Motor Learning and Development*, *6*(1), 81–100. Retrieved from https://journals.humankinetics.com/view/journals/jmld/6/1/article-p81.xml

Boxing GB. (2019). Overview of Boxing | GB Boxing. Retrieved August 5, 2020, from https://www.gbboxing.org.uk/overview-of-boxing/

Bradley, E. J., Board, L., Hogg, B., & Archer, D. T. (2020). Quantification of Movement Characteristics in Women's English Premier Elite Domestic Rugby Union. *Journal of Human Kinetics*, *72*(1), 185–194. Retrieved from https://www.cem.org/effect-size-

Broglio, S. P., Lapointe, A., O'Connor, K. L., & McCrea, M. (2017). Head Impact Density: A Model To Explain the Elusive Concussion Threshold. *Journal of Neurotrauma*, *34*(19), 2675–2683. Retrieved from http://www.liebertpub.com/doi/10.1089/neu.2016.4767

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.

Brown, J. C., Starling, L. T., Stokes, K., Viviers, P., Jordaan, E., Surmon, S., & Derman, E. W. (2019). High Concussion Rate in Student Community Rugby Union Players During the 2018 Season: Implications for Future Research Directions. *Frontiers in Human Neuroscience*, *13*. Retrieved from /pmc/articles/PMC6904273/?report=abstract

Bruinvels, G., Burden, R. J., McGregor, A. J., Ackerman, K. E., Dooley, M., Richards, T., & Pedlar, C. (2017, March 1). Sport, exercise and the menstrual cycle: Where is the research? *British Journal of Sports Medicine*, Vol. 51, pp. 487–488. BMJ Publishing Group.

Buckley, T. A. (2014). Acute and Lingering Impairments in Post-concussion Postural Control. In *Concussions in Athletics* (pp. 139–165). Springer New York.

Buckley, T. A., Oldham, J. R., & Caccese, J. B. (2016, March 1). Postural control deficits identify lingering post-concussion neurological deficits. *Journal of Sport and Health Science*, Vol. 5, pp. 61–69. Elsevier B.V.

Burger, N., Lambert, M. I., Viljoen, W., Brown, J. C., Readhead, C., & Hendricks, S. (2015). Tackle technique and tackle-related injuries in high-level South African Rugby Union under-18 players: real-match video analysis. *Br J Sports Med*, *10*(1136). Retrieved from http://bjsm.bmj.com/

Bussey, M. D., 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.

Buvinic, M., & Levine, R. (2016). Closing the gender data gap. *Significance*, *13*(2), 34–37. Retrieved from http://doi.wiley.com/10.1111/j.1740-9713.2016.00899.x

Caccese, J. B., Buckley, T. A., Tierney, R. T., Arbogast, K. B., Rose, W. C., Glutting, J. J., & Kaminski, T. W. (2017). Head and neck size and neck strength predict linear and rotational acceleration during purposeful soccer heading. *Sports Biomechanics*, 1–15. Retrieved from https://www.tandfonline.com/doi/full/10.1080/14763141.2017.1360385

Cárcamo, C., Moreno, A., & del Barrio, C. (2020). Girls Do Not Sweat: the Development of Gender Stereotypes in Physical Education in Primary School. *Human Arenas*, 1–22. Retrieved from https://doi.org/10.1007/s42087-020-00118-6

Churchill, N. W., Hutchison, M. G., Graham, S. J., & Schweizer, T. A. (2020). Baseline vs. cross-sectional MRI of concussion: distinct brain patterns in white matter and cerebral blood flow. *Scientific Reports*, *10*(1), 1–13.

Cole, E. E. (2018). *Exploring the relationship between neck strength, anthropometry and symptom scores on concussion risk and recovery in university athletes*. (Master of Science Thesis), McMaster University, Hamilton, Ontario, Canada

Collins, C. L., Fletcher, E. N., Fields, S. K., Kluchurosky, L., Rohrkemper, M. K., Comstock, R. D., & Cantu, R. C. (2014). Neck Strength: A Protective Factor Reducing Risk for Concussion in High School Sports. *Journal of Primary Prevention*, *35*(5), 309–319.

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. Retrieved from http://www.tandfonline.com/doi/abs/10.1080/17461391.2014.911354

Cournoyer, J., & Hoshizaki, T. B. (2019). Head dynamic response and brain tissue deformation for boxing punches with and without loss of consciousness. *Clinical Biomechanics*, *67*, 96–101.

Covassin, T., Moran, R., & Elbin, R. J. (2016, March 1). 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*, Vol. 51, pp. 189–194. National Athletic Trainers’ Association Inc.

Covassin, T., Stearne, D., & Elbin, R. (2008). Concussion history and postconcussion neurocognitive performance and symptoms in collegiate athletes. *Journal of Athletic Training*, *43*(2), 119–124. Retrieved from www.nata.org/jat

Crews, J., Braude, S., Stephenson, C., & Clardy, T. (2020). *(PDF) The Ethogram and Animal Behavior Research*. Retrieved from https://www.researchgate.net/publication/299586471_The_Ethogram_and_Animal_Behavior_Research

Criado Perez, P. (2019). *Invisible Women: Exposing Data Bias in a World Designed for Men - Caroline Criado Perez - Google Books*. Retrieved from https://books.google.co.uk/books?hl=en&lr=&id=MKZYDwAAQBAJ&oi=fnd&pg=PT8&ots=PqQGT1X-Qk&sig=2FsAcPkSi0gRgDeBjDTwicSlqSE&redir_esc=y#v=onepage&q&f=false

Cross, M. J., Tucker, R., Raftery, M., Hester, B., Williams, S., Stokes, K. A., … 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.

Cummins, C., Melinz, J., King, D., Sanctuary, C., & Murphy, A. (2020, May 1). Call to action: A collaborative framework to better support female rugby league players. *British Journal of Sports Medicine*, Vol. 54, pp. 501–502. Retrieved from http://bjsm.bmj.com/

Cunningham, J., Broglio, S. P., O’Grady, M., & Wilson, F. (2020, February 1). History of sport-related concussion and long-term clinical cognitive health outcomes in retired athletes: A systematic review. *Journal of Athletic Training*, Vol. 55, pp. 132–158. Retrieved from http://dx.doi.org/10.4085/1062-6050-297-18.S1

Davidow, D., Quarrie, K., Viljoen, W., Burger, N., Readhead, C., Lambert, M., … Hendricks, S. (2018). Tackle technique of rugby union players during head impact tackles compared to injury free tackles. *Journal of Science and Medicine in Sport*, *21*(10), 1025–1031.

De Rosario, H., Page, A., Besa, A., Mata, V., & Conejero, E. (2012). Kinematic description of soft tissue artifacts: Quantifying rigid versus deformation components and their relation with bone motion. *Medical and Biological Engineering and Computing*, *50*(11), 1173–1181. Retrieved from https://link.springer.com/article/10.1007/s11517-012-0978-5

DeGoede, K. M., Ashton-Miller, J. A., & Schultz, A. B. (2003, July 1). Fall-related upper body injuries in the older adult: A review of the biomechanical issues. *Journal of Biomechanics*, Vol. 36, pp. 1043–1053. Retrieved from https://pubmed.ncbi.nlm.nih.gov/12757814/

den Hollander, S., Lambert, M., Jones, B., & Hendricks, S. (2020). Knowledge of the importance of proper tackle contact techniques does not translate to proper tackle contact technique for injury prevention and performance - ProQuest. *British Journal of Sports Medicine*, *54*. Retrieved from https://search.proquest.com/docview/2371193458?pq-origsite=gscholar&fromopenview=true

Dixit, R., Ross, J. L., Goldman, Y. E., & Holzbaur, E. L. F. (2008). Differential regulation of dynein and kinesin motor proteins by tau. *Science*, *319*(5866), 1086–1089.

Dollé, J. P., Jaye, A., Anderson, S. A., Ahmadzadeh, H., Shenoy, V. B., & Smith, D. H. (2018). Newfound sex differences in axonal structure underlie differential outcomes from in vitro traumatic axonal injury. *Experimental Neurology*, *300*, 121–134.

Eckner, J. T., O’Connor, K. L., Broglio, S. P., & Ashton-Miller, J. A. (2018). Comparison of Head Impact Exposure Between Male and Female High School Ice Hockey Athletes. *American Journal of Sports Medicine*, *46*(9), 2253–2262. Retrieved from http://journals.sagepub.com/doi/10.1177/0363546518777244

Eckner, J. T., Oh, Y. K., Joshi, M. S., Richardson, J. K., & Ashton-Miller, J. A. (2014). Effect of neck muscle strength and anticipatory cervical muscle activation on the kinematic response of the head to impulsive loads. *The American Journal of Sports Medicine*, *42*(3), 566–576. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/24488820

Eime, R. M., Young, J. A., Harvey, J. T., Charity, M. J., & Payne, W. R. (2013). A systematic review of the psychological and social benefits of participation in sport for adults: Informing development of a conceptual model of health through sport. *International Journal of Behavioral Nutrition and Physical Activity*, *10*(1), 1–14.

Ellemberg, D., Leclerc, S., Couture, S., & Daigle, C. (2007). Prolonged neuropsychological impairments following a first concussion in female university soccer athletes. *Clinical Journal of Sport Medicine*, *17*(5), 369–374. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/17873549

England Boxing. (2020). England Boxing Rule Book. Retrieved August 6, 2020, from https://www.englandboxing.org/rules-regs-resources/rule-book/

England Rugby. (2012). *Age Grade Rugby*, Rugby Summer 2018, Version 3 Rugby Football Union. Retrived from https://www.englandrugby.com/participation/coaching/age-grade-rugby

England Rugby. (2017). *This is England Women’s Rugby: A plan to get 100,000 females involved in rugby*. Retrieved from http://files.pitchero.com/counties/34/1486657099.pdf

Esopenko, C., Simonds, A. H., & Anderson, E. Z. (2018). The synergistic effect of concussions and aging in women? Disparities and perspectives on moving forward. *Concussion*, *3*(2), CNC55.

Ewers, N. (2020). *Is it worth the hit? Examining the cognitive effects of subconcussive impacts in sport using event related potentials*. Retrieved from https://macsphere.mcmaster.ca/handle/11375/25519

Fann, J. R., Ribe, A. R., Pedersen, H. S., Fenger-Grøn, M., Christensen, J., Benros, M. E., & Vestergaard, M. (2018). Long-term risk of dementia among people with traumatic brain injury in Denmark: a population-based observational cohort study. *The Lancet Psychiatry*, *5*(5), 424–431.

Fernández-Pérez, A. M., Villaverde-Gutiérrez, C., Mora-Sánchez, A., Alonso-Blanco, C., Sterling, M., & Fernández-De-Las-Peñas, C. (2012). Muscle trigger points, pressure pain threshold, and cervical range of motion in patients with high level of disability related to acute whiplash injury. *Journal of Orthopaedic and Sports Physical Therapy*, *42*(7), 634–641. Retrieved from www.jospt.org

Fields, S. K., & Comstock, R. D. (2016). Why American Women Play Rugby. *Women* *in Sport and Physical Activity Journal*, *17*(2), 8–18.

Fillingim, R. B., King, C. D., Ribeiro-Dasilva, M. C., Rahim-Williams, B., & Riley, J. L. (2009, May). Sex, Gender, and Pain: A Review of Recent Clinical and Experimental Findings. *Journal of Pain*, Vol. 10, pp. 447–485.

Fuller, C. W., Brooks, J. H. M., Cancea, R. J., Hall, J., & Kemp, S. P. T. (2007). Contact events in rugby union and their propensity to cause injury. *British Journal of Sports Medicine*, *41*(12), 862–867.

Fuller, G. W., Kemp, S. P. T., & Raftery, M. (2017). The accuracy and reproducibility of video assessment in the pitch-side management of concussion in elite rugby. *Journal of Science and Medicine in Sport*, *20*(3), 246–249.

Fuller, G. W., Tucker, R., Starling, L., Falvey, E., Douglas, M., & Raftery, M. (n.d.). *The performance of the World Rugby Head Injury Assessment Screening Tool: a diagnostic accuracy study*. Retrieved from https://doi.org/10.1186/s40798-019-0231-y

Gabbett, T. J. (2007). Physiological and anthropometric characteristics of elite women rugby league players. *Journal of Strength and Conditioning Research*, *21*(3), 875–881.

Gabbett, T., & Kelly, J. (2007a). Does Fast Defensive Line Speed Influence Tackling Proficiency in Collision Sport Athletes? *International Journal of Sports Science & Coaching*, *2*(4), 467–472. Retrieved from http://journals.sagepub.com/doi/10.1260/174795407783359731

Gabbett, T., & Kelly, J. (2007b). Does Fast Defensive Line Speed Influence Tackling Proficiency in Collision Sport Athletes? *International Journal of Sports Science & Coaching*, *2*(4), 467–472. Retrieved from http://journals.sagepub.com/doi/10.1260/174795407783359731

Gallagher, V., Kramer, N., Abbott, K., Alexander, J., Breiter, H., Herrold, A., … Reilly, J. (2018a). The effects of sex differences and hormonal contraception on outcomes after collegiate sports-related concussion. *Journal of Neurotrauma*, *35*(11), 1242–1247. Retrieved from http://www.liebertpub.com/doi/10.1089/neu.2017.5453

Gallagher, V., Kramer, N., Abbott, K., Alexander, J., Breiter, H., Herrold, A., … Reilly, J. (2018b). The Effects of Sex Differences and Hormonal Contraception on Outcomes after Collegiate Sports-Related Concussion. *Journal of Neurotrauma*, *35*(11), 1242–1247. Retrieved from http://www.liebertpub.com/doi/10.1089/neu.2017.5453

Gardner, A., Iverson, G. L., Levi, C. R., Schofield, P. W., Kay-Lambkin, F., Kohler, R. M. N., & Stanwell, P. (2015, April 1). A systematic review of concussion in rugby league. *British Journal of Sports Medicine*, Vol. 49, pp. 495–498. Retrieved from https://pubmed.ncbi.nlm.nih.gov/24723636/

Gardner, A. J., Iverson, G. L., Huw Williams, W., Baker, S., & Stanwell, P. (2014). *A Systematic Review and Meta-Analysis of Concussion in Rugby Union*.

Gardner, A. J., Iverson, G. L., Williams, W. H., Baker, S., & Stanwell, P. (2014a, November 25). A systematic review and meta-analysis of concussion in Rugby

Union. *Sports Medicine*, Vol. 44, pp. 1717–1731. Springer International Publishing.

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

Geeson-Brown, T., Jones, B., Till, K., Chantler, S., & Deighton, K. (2020). Body composition differences by age and playing standard in male rugby union and rugby league: A systematic review and meta-analysis. *Journal of Sports Sciences*, *00*. Retrieved from https://www.tandfonline.com/action/journalInformation?journalCode=rjsp20

Ghajari, M., Hellyer, P. J., & Sharp, D. J. (2017). Computational modelling of traumatic brain injury predicts the location of chronic traumatic encephalopathy pathology. *Brain*, *140*(2), 333–343. Retrieved from https://academic.oup.com/brain/article/140/2/333/2770746

Ghasemi, A., & Zahediasl, S. (2012). Normality tests for statistical analysis: A guide for non-statisticians. *International Journal of Endocrinology and Metabolism*, *10*(2), 486–489. Retrieved from /pmc/articles/PMC3693611/?report=abstract

Golden, C. J., & Zusman, M. R. (2019). *Chronic Traumatic Encephalopathy (CTE)*. Retrieved from http://link.springer.com/10.1007/978-3-030-23288-7

Greenwald, R. M., Chu, J. J., Crisco, J. J., & Finkelstein, J. A. (2003). *Head Impact Telemetry System (HITS^{TM}) For Measurement Of Head Acceleration In The Field*

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

Gunasekaran, P., Hodge, C., Pearce, A., King, D., & Fraser, C. (2020, January 2). A review of concussion diagnosis and management in Australian professional sporting codes. *Physician and Sportsmedicine*, Vol. 48, pp. 1–7. Retrieved from https://www.tandfonline.com/doi/abs/10.1080/00913847.2019.1624656

Guskiewicz, K. M., McCrea, M., Marshall, S. W., Cantu, R. C., Randolph, C., Barr, W., … Kelly, J. P. (2003). Cumulative Effects Associated with Recurrent Concussion in Collegiate Football Players: The NCAA Concussion Study. *Journal of the American Medical Association*, *290*(19), 2549–2555. Retrieved from https://jamanetwork.com/

Gutierrez-Garcia, C., Astrain, I., Izquierdo, E., Gomez-Alonso, M. T., & Yague, J. M. (2018). Effects of judo participation in children: A systematic review. *Ido Movement for Culture*, *18*(4), 63–73.

Gutierrez, G. M., Conte, C., & Lightbourne, K. (2014). The relationship between impact force, neck strength, and neurocognitive performance in soccer heading in adolescent females. *Pediatric Exercise Science*, *26*(1), 33–40.

Hancock Craig Barden, M., Kemp, S., Brown, R., Stokes, K., Roberts, S., McKay, C., & Barden, C. (2018). *Youth Rugby Injury Surveillance Project Season Report*

2017-18.

Hardy, W. N., Mason, M. J., Foster, C. D., Shah, C. S., Kopacz, J. M., Yang, K. H., … Tashman, S. (2007). A study of the response of the human cadaver head to impact. *Stapp Car Crash Journal*, *51*, 17–80. Retrieved from /pmc/articles/PMC2474809/?report=abstract

Hendricks, S., O'Connor, S., Lambert, M., Brown, J. C., Burger, N., Mc Fie, S., … Viljoen, W. (2016). Video analysis of concussion injury mechanism in under-18 rugby. *BMJ Open Sport & Exercise Medicine*, *2*(1), e000053. Retrieved from http://dx.doi.org/10.1136/bmjsem-2015-000053

Hendricks, S., Till, K., Den Hollander, S., Savage, T. N., Roberts, S. P., Tierney, G., … Jones, B. (2020). Consensus on a video analysis framework of descriptors and definitions by the Rugby Union Video Analysis Consensus group Consensus statement. *Br J Sports Med*, *54*, 13. Retrieved from http://bjsm.bmj.com/

Henry, L. C., Elbin, R. J., Collins, M. W., Marchetti, G., & Kontos, A. P. (2016). Examining Recovery Trajectories After Sport-Related Concussion With a Multimodal Clinical Assessment Approach. *Neurosurgery*, *78*(2), 232–241. Retrieved from https://academic.oup.com/neurosurgery/article/78/2/232/2453658

Herman, D. C., Jones, D., Harrison, A., Moser, M., Tillman, S., Farmer, K., … Chmielewski, T. L. (2017). Concussion May Increase the Risk of Subsequent Lower Extremity Musculoskeletal Injury in Collegiate Athletes. *Sports Medicine*, *47*(5), 1003–1010.

Hickling, A., Mallory, K. D., Wilson, K. E., Del Fernandes, R., Fuselli, P., Reed, N., … Zemek, R. (2020). The youth concussion awareness network (You-CAN) - A school-based peer-led intervention to improve concussion reporting and social support: The protocol for a cluster randomized trial. *BMC Public Health*, *20*(1), 1–10.

Hiploylee, C., Dufort, P. A., Davis, H. S., Wennberg, R. A., Tartaglia, M. C., Mikulis, D., … Tator, C. H. (2017). Longitudinal Study of Postconcussion Syndrome: Not Everyone Recovers. *Journal of Neurotrauma*, *34*(8), 1511–1523. Retrieved from http://www.liebertpub.com/doi/10.1089/neu.2016.4677

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. Retrieved from http://bjsm.bmj.com/

Ho, F. K. W., Louie, L. H. T., Chow, C. B., Wong, W. H. S., & Ip, P. (2015). Physical activity improves mental health through resilience in Hong Kong Chinese adolescents. *BMC Pediatrics*, *15*(1), 48. Retrieved from http://bmcpediatr.biomedcentral.com/articles/10.1186/s12887-015-0365-0

Hobbs, J., Young, J., & Bailes, J. (2016). Sports-related concussions: diagnosis, complications, and current management strategies in: Neurosurgical Focus Volume 40 Issue 4 (2016). *Journal of Neurosurgery*, *40*(4). Retrieved from https://thejns.org/focus/view/journals/neurosurg-focus/40/4/article-pE5.xml

Hollis, S. J., Stevenson, M. R., McIntosh, A. S., Shores, E. A., & Finch, C. F. (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. Retrieved from http://bjsm.bmj.com/

Holman, L., Stuart-Fox, D., & Hauser, C. E. (2018). The gender gap in science: How long until women are equally represented? *PLOS Biology*, *16*(4), e2004956. Retrieved from https://dx.plos.org/10.1371/journal.pbio.2004956

Honda, J., Chang, S. H., & Kim, K. (2018). The effects of vision training, neck musculature strength, and reaction time on concussions in an athletic population. *Journal of Exercise Rehabilitation*, *14*(5), 706–712.

Howell, D. R., Osternig, L. R., Koester, M. C., & Chou, L. S. (2014). The effect of cognitive task complexity on gait stability in adolescents following concussion. *Experimental Brain Research*, *232*(6), 1773–1782.

Hrysomallis, C. (2016, August 1). Neck Muscular Strength, Training, Performance and Sport Injury Risk: A Review. *Sports Medicine*, Vol. 46, pp. 1111–1124. Retrieved from https://link.springer.com/article/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.

Hume, P. A., Theadom, A., Lewis, G. N., Quarrie, K. L., Brown, S. R., Hill, R., & Marshall, S. W. (2017). 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*, *47*(6), 1209–1220.

Hunter, A. M., Wu, Y.-N., Palmer, D., Brown, J. C., Starling, L. T., Stokes, K., … Derman, E. W. (2019). *High Concussion Rate in Student Community Rugby Union Players During the 2018 Season: Implications for Future Research Directions*. Retrieved from www.frontiersin.org

Hurley, K. S., Flippin, K. J., Blom, L. C., Bolin, J. E., Hoover, D. L., & Judge, L. W. (2018). Practices, Perceived Benefits, and Barriers to Resistance Training Among Women Enrolled in College. *International Journal of Exercise Science*, *11*(5), 226–238. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/29795737

Hwang, S., Ma, L., Kawata, K., Tierney, R., & Jeka, J. J. (2017). Vestibular dysfunction after subconcussive head impact. *Journal of Neurotrauma*, *34*(1), 8–15.

Inside the Affiliate. (2014). The Benefits of Introductory Programs at Affiliates - Blog - Inside the Affiliate. Retrieved September 20, 2020, from http://www.insidetheaffiliate.com/blog/2014/1/13/the-benefits-of-introductory-programs-at-affiliates.html

Jadischke, R., Viano, D. C., Dau, N., King, A. I., & McCarthy, J. (2013). On the accuracy of the head impact telemetry (hit) system used in football helmets. *Journal of Biomechanics*, *46*(13), 2310–2315.

Jaffee, M. S., Winter, W. C., Jones, C. C., & Ling, G. (2015, February 1). Sleep disturbances in athletic concussion. *Brain Injury*, Vol. 29, pp. 221–227. Retrieved from http://www.tandfonline.com/doi/full/10.3109/02699052.2014.983978

Johnston, K. M., Ptito, A., Chankowsky, J., & Chen, J. K. (2001). New frontiers in diagnostic imaging in concussive head injury. *Clinical Journal of Sport Medicine, 11*(3), 166–175. Retrieved from https://pubmed.ncbi.nlm.nih.gov/11495321/

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. Retrieved from http://journals.lww.com/00124278-201605000-00019

Kamitani, T., Nimura, Y., Nagahiro, S., Miyazaki, S., & Tomatsu, T. (2013). Catastrophic head and neck injuries in judo players in Japan from 2003 to 2010. *American Journal of Sports Medicine*, *41*(8), 1915–1921.

Karton, C., Hoshizaki, B., & Gilchrist, M. D. (2020). *A novel repetitive head impact exposure measurement tool differentiates player position in national football League*. Retrieved from https://doi.org/10.1038/s41598-019-54874-9

Kay, M. C., Register-Mihalik, J. K., Ford, C. B., Williams, R. M., & Valovich McLeod, T. C. (2017). Parents' and Child's Concussion History as Predictors of Parental Attitudes and Knowledge of Concussion Recognition and Response. *Orthopaedic Journal of Sports Medicine*, *5*(12), 232596711774237. Retrieved from http://journals.sagepub.com/doi/10.1177/2325967117742370

Kemp, S., Brown, R., Stokes, K., & Roberts, S. (2018). *BUCS Super Rugby Injury Surveillance Project*.

Kemp, S., Fairweather, C., Williams, S., Stokes, K., West, S., Phillips, T., & Bears, B. (2018). *RFU: Women's Rugby Injury Surveillance Project 2017/18*.

Kemp, S., Fairweather, C., Williams, S., Stokes, K., West, S., Phillips, T., … Henderson, L. (2018). *Women's Rugby Injury Surveillance Project. Season Report 2017/18*. *1*, 12–16.

Kent, R., Shaw, G., Lessley, D., Crandall, J., Kallieris, D., & Svensson, M. (2003). Comparison of Belted Hybrid III, THOR, and Cadaver Thoracic Responses in Oblique Frontal and Full Frontal Sled Tests. *SAE Transactions,* Vol. 112, pp. 71–84. Retrieved from https://www.jstor.org/stable/44745377

Kerr, H. A., Ledet, E. H., Ata, A., Newitt, J. L., Santa Barbara, M., Kahanda, M., & Sperry Schlueter, E. (2018). Does instructional video footage improve tackle technique? *International Journal of Sports Science & Coaching*, *13*(1), 3–15. Retrieved from http://journals.sagepub.com/doi/10.1177/1747954117711867

Kerr, Z. Y., Marshall, S. W., Simon, J. E., Hayden, R., Snook, E. M., Dodge, T., … Dompier, T. P. (2015). Injury Rates in Age-Only Versus Age-and-Weight Playing Standard Conditions in American Youth Football. *Orthopaedic Journal of Sports Medicine, 3*(9). Retrieved from /pmc/articles/PMC4622300/?report=abstract

Kian, E. M., Vincent, J., & Mondello, M. (2008, June 1). Masculine hegemonie hoops: An analysis of media coverage of march madness. *Sociology of Sport Journal*, Vol. 25, pp. 223–242. Retrieved from https://journals.humankinetics.com/view/journals/ssj/25/2/article-p223.xml

King, D. A., Hume, P. A., Gissane, C., Kieser, D. C., & Clark, T. N. (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*.

King, D. A., Hume, P. A., Milburn, P. D., & Guttenbeil, D. (2010). Match and training injuries in rugby league: A review of published studies. *Sports Medicine*, Vol. 40, pp. 163–178. Retrieved from https://pubmed.ncbi.nlm.nih.gov/20092367/

King, D. A., Hume, P., Gissane, C., & Clark, T. (2017). *Measurement of Head Impacts in a Senior Amateur Rugby League Team with an Instrumented Patch: Exploratory Analysis*. Retrieved from https://www.arcjournals.org/journal-of-research-in-sports-medicine/volume-2-issue-1/

King, D., Hume, P., Cummins, C., Clark, T., 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,* 024-037.

King, D., Hume, P., Gissane, C., Brughelli, M., & Clark, T. (2016). The Influence of Head Impact Threshold for Reporting Data in Contact and Collision Sports: Systematic Review and Original Data Analysis. *Sports Medicine*, *46*(2), 151–169.

King, Doug, Hume, P. A., Brughelli, M., & Gissane, C. (2015a). Instrumented mouthguard acceleration analyses for head impacts in amateur rugby union players over a season of matches. *The American Journal of Sports Medicine*, *43*(3), 614–624. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/25535096

King, Doug, Hume, P. A., Brughelli, M., & Gissane, C. (2015b). 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. Retrieved from http://journals.sagepub.com/doi/10.1177/0363546514560876

King, Doug, Hume, P., Cummins, C., Pearce, A., Clark, T., Foskett, A., & Barnes, M. (2019, October 1). Match and Training Injuries in Women's Rugby Union: A Systematic Review of Published Studies. *Sports Medicine*, Vol. 49, pp. 1559–1574. Retrieved from https://doi.org/10.1007/s40279-019-01151-4

King, Doug, Hume, P., Gissane, C., & Clark, T. (2017). Head impacts in a junior rugby league team measured with a wireless head impact sensor: an exploratory analysis. *Journal of Neurosurgery: Pediatrics*, *19*(1), 13–23. Retrieved from https://thejns.org/view/journals/j-neurosurg-pediatr/19/1/article-p13.xml

Kleiven, S. (2013). Why Most Traumatic Brain Injuries are Not Caused by Linear Acceleration but Skull Fractures are. *Frontiers in Bioengineering and Biotechnology*, *1*, 15. Retrieved from http://journal.frontiersin.org/article/10.3389/fbioe.2013.00015/abstract

Kurland, D., Hong, C., Aarabi, B., Gerzanich, V., & Simard, J. M. (2012, January 1). Hemorrhagic progression of a contusion after traumatic brain injury: A review. *Journal of Neurotrauma*, Vol. 29, pp. 19–31. Retrieved from https://www.liebertpub.com/doi/abs/10.1089/neu.2011.2122

Langevin, T. L., Antonoff, D., Renodin, C., Shellene, E., Spahr, L., Marsh, W. A., & Rosene, J. M. (2020). Head impact exposures in women's collegiate rugby. *Physician and Sportsmedicine*, 1–6. Retrieved from https://www.tandfonline.com/doi/full/10.1080/00913847.2020.1770568

Lichtman, J. H., Leifheit, E. C., Safdar, B., Bao, H., Krumholz, H. M., Lorenze, N. P., … D’Onofrio, G. (2018). Sex Differences in the Presentation and Perception of Symptoms Among Young Patients With Myocardial Infarction: Evidence from the VIRGO Study (Variation in Recovery: Role of Gender on Outcomes of Young AMI Patients). *Circulation*, *137*(8), 781–790. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/29459463%0Ahttp://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC5822747

Lind, B., Sihlbom, H., Nordwall, A., & Malchau, H. (1989). Normal range of motion of the cervical spine. *Archives of Physical Medicine and Rehabilitation*, *70*(9), 692–695.

Lindsay, A., Draper, N., Lewis, J., Gieseg, S. P., & Gill, N. (2015a). Positional demands of professional rugby. *European Journal of Sport Science*, *15*(6), 480–487. Retrieved from http://www.tandfonline.com/doi/full/10.1080/17461391.2015.1025858

Lindsay, A., Draper, N., Lewis, J., Gieseg, S. P., & Gill, N. (2015b). Positional demands of professional rugby. *European Journal of Sport Science*, *15*(6), 480–487. Retrieved from http://www.tandfonline.com/doi/full/10.1080/17461391.2015.1025858

Madrigal, L., Robbins, J., Gill, D. L., & Wurst, K. (2015). A Pilot Study Investigating the Reasons for Playing Through Pain and Injury: Emerging Themes in Men’s and Women’s Collegiate Rugby. *Sport Psychologist*, *29*(4), 310–318.

Mainwaring, L., Ferdinand Pennock, K. M., Mylabathula, S., & Alavie, B. Z. (2018). Subconcussive head impacts in sport: A systematic review of the evidence. *International Journal of Psychophysiology*, *132*, 39–54.

Margulies, S. S., & Thibault, L. E. (1992). A proposed tolerance criterion for diffuse axonal injury in man. *Journal of Biomechanics*, *25*(8), 917–923.

Martins, J., Marques, A., Loureiro, N., Da Costa, F. C., Diniz, J., & De Matos, M. G. (2019). Trends and age-related changes of physical activity among Portuguese adolescent girls from 2002-2014: Highlights from the health behavior in school-aged children study. *Journal of Physical Activity and Health*, *16*(4), 281–287. Retrieved from https://journals.humankinetics.com/view/journals/jpah/16/4/article-p281.xml

Master, C. L., Master, S. R., Wiebe, D. J., Storey, E. P., Lockyer, J. E., Podolak, O. E., & Grady, M. F. (2018). Vision and Vestibular System Dysfunction Predicts Prolonged Concussion Recovery in Children. *Clinical Journal of Sport Medicine*, *28*(2), 139–145.

McCrory, P., 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. Retrieved from http://bjsm.bmj.com/

McGuine, T. A., Pfaller, A., Kliethermes, S., Schwarz, A., Hetzel, S., Hammer, E., & Broglio, S. (2019). The Effect of Sport-Related Concussion Injuries on Concussion Symptoms and Health-Related Quality of Life in Male and Female

Adolescent Athletes: A Prospective Study. *The American Journal of Sports Medicine*, *47*(14), 3514–3520. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/31647876

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. Retrieved from https://academic.oup.com/brain/article-lookup/doi/10.1093/brain/aws307

McPherson, A. L., Nagai, T., Webster, K. E., & Hewett, T. E. (2019, June 1). Musculoskeletal Injury Risk After Sport-Related Concussion: A Systematic Review and Meta-analysis. *American Journal of Sports Medicine*, Vol. 47, pp. 1754–1762. Retrieved from http://journals.sagepub.com/doi/10.1177/0363546518785901

Meehan, W. P., Mannix, R. C., Oêbrien, M. J., & Collins, M. W. (2013). The prevalence of undiagnosed concussions in athletes. *Clinical Journal of Sport Medicine*, *23*(5), 339–342.

Merriaux, P., Dupuis, Y., Boutteau, R., Vasseur, P., & Savatier, X. (2017). A Study of Vicon System Positioning Performance. *Sensors*, *17*(7), 1591. Retrieved from http://www.mdpi.com/1424-8220/17/7/1591

Mihalik, J. P., Blackburn, J. T., Greenwald, R. M., Cantu, R. C., Marshall, S. W., & Guskiewicz, K. M. (2010). Collision type and player anticipation affect head impact severity among youth ice hockey players. *Pediatrics*, *125*(6).

Miyashita, T. L., Diakogeorgiou, E., & VanderVegt, C. (2016). Gender Differences in Concussion Reporting Among High School Athletes. *Sports Health*, *8*(4), 359–363. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/27233957

Moore, D. F., Jaffee, M., Ling, G., & Radovitzky, R. (2020). Overview of Traumatic Brain Injury (TBI). In *Traumatic Brain Injury* (pp. 1–13). Springer International Publishing.

Morgan, P. (2016). *Team Resilience in Competitive Sport*.

National Assembly for Wales, & Health, S. C. and S. C. (2019). *Physical Activity of Children and Young People*. Retrieved from www.assembly.wales

Nauman, E. A., Talavage, T. M., & Auerbach, P. S. (2020). Mitigating the Consequences of Subconcussive Head Injuries. *Annual Review of Biomedical Engineering*, *22*(1), annurev-bioeng-091219-053447. Retrieved from https://www.annualreviews.org/doi/10.1146/annurev-bioeng-091219-053447

Nevins, D., Smith, L., & Kensrud, J. (2015). Laboratory evaluation of wireless head impact sensor. *Procedia Engineering*, *112*, 175–179. Elsevier Ltd.

New Zealand Rugby. (2020). Black Ferns: About the Team. Retreieved from: https://www.allblacks.com/teams/black-ferns/

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

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

O'Connor, K. L., Rowson, S., Duma, S. M., & Broglio, S. P. (2017, March 1). Head-impact-measurement devices: A systematic review. *Journal of Athletic Training*, Vol. 52, pp. 206–227. Retrieved from http://meridian.allenpress.com/jat/article-pdf/52/3/206/2309559/1062-6050_52_2_05.pdf

Pearce, A. J., Rist, B., Fraser, C. L., Cohen, A., & Maller, J. J. (2018). Neurophysiological and cognitive impairment following repeated sports concussion injuries in retired professional rugby league players. *Brain Injury*, *32*(4), 498–505.

Peters, A., Galna, B., Sangeux, M., Morris, M., & Baker, R. (2010, January). Quantification of soft tissue artifact in lower limb human motion analysis: A systematic review. *Gait and Posture*, Vol. 31, pp. 1–8. Retrieved from https://pubmed.ncbi.nlm.nih.gov/19853455/

Pocecco, E., Ruedl, G., Stankovic, N., Sterkowicz, S., Del Vecchio, F. B., Gutiérrez-García, C., … Burtscher, M. (2013, December 1). Injuries in judo: A systematic literature review including suggestions for prevention. *British Journal of Sports Medicine*, Vol. 47, pp. 1139–1143. Retrieved from http://bjsm.bmj.com/

Post, A., Rousseau, P., Kendall, M., Walsh, E. S., & Hoshizaki, T. B. (2015). Determination of high-risk impact sites on a Hybrid III headform by finite element analysis. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*, *229*(1), 17–27. Retrieved from http://journals.sagepub.com/doi/10.1177/1754337114551444

Precht, W. (2012). Neuronal Operations in the Vestibular System. In *Neuronal operations in the vestibular system* (2nd ed., Vol. 2). Retrieved from https://books.google.co.uk/books?hl=en&lr=&id=CCLsCAAAQBAJ&oi=fnd&pg=PA1&dq=function+of+vestibular+system&ots=BALNeWmt49&sig=HTKIfakUEWdvVB9-4-PwR4HJUoo&redir_esc=y#v=onepage&q=function of vestibular system&f=false

Preiss-Farzanegan, S. J., Chapman, B., Wong, T. M., Wu, J., & Bazarian, J. J. (2009). The Relationship Between Gender and Postconcussion Symptoms After Sport-Related Mild Traumatic Brain Injury. *PM and R*, *1*(3), 245–253.

Prien, A., Grafe, A., Rössler, R., Junge, A., & Verhagen, E. (2018, April 1). Epidemiology of Head Injuries Focusing on Concussions in Team Contact Sports: A Systematic Review. *Sports Medicine*, Vol. 48, pp. 953–969. Springer International Publishing.

Prins, M. L., Alexander, D., Giza, C. C., & Hovda, D. A. (2013). Repeated mild traumatic brain injury: Mechanisms of cerebral vulnerability. *Journal of Neurotrauma*, *30*(1), 30–38.

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

Rafferty, J., Ranson, C., Oatley, G., Mostafa, M., Mathema, P., Crick, T., & Moore, I. S. (2019). On average, a professional rugby union player is more likely than not to sustain a concussion after 25 matches. *British Journal of Sports Medicine*, *53*(15), 969–973.

Rayner, M. (2017). *Rugby Union and Professionalisation: Elite Player Perspectives - Mike Rayner - Google Books*. Retrieved from https://books.google.co.uk/books?hl=en&lr=&id=MbpDDwAAQBAJ&oi=fnd&pg=PT15&dq=The+Professionalisation+of+Rugby+Union+in+England,&ots=6y5l6F85qM&sig=dRQ4ZYR1VZBfFi0qOCwR8ZLutJU&redir_esc=y#v=onepage&q=The Professionalisation of Rugby Union in England%2C&f=false

Read, D., Weaving, D., Phibbs, P., Darrall-Jones, J., Roe, G., Weakley, J., … Jones, B. (2017). Movement and physical demands of school and university rugby union match-play in England. *BMJ Open Sport and Exercise Medicine*, *2*(1).

Reyes, A. C., Chaves, R., Baxter-Jones, A. D. G., Vasconcelos, O., Tani, G., & Maia, J. (2018). A mixed-longitudinal study of children’s growth, motor development and cognition. Design, methods and baseline results on sex-differences. *Annals of Human Biology*, *45*(5), 376–385. Retrieved from https://www.tandfonline.com/doi/abs/10.1080/03014460.2018.1511828

Roberts, S., Kemp, S., Morgan, L., & Stokes, K. (2020). Tackle characteristics associated with concussion in British university level rugby union *British Journal of Sports Medicine* 54, no. Suppl 1

Rugby All Nations. (2020). Rugby Féminin - Wales Vs France - 6 Nations 2020.

Rugby Football Union. (2014). *RFU Community Rugby Injury Surveillance Project CRISP 2013-2014 Season Report*. Retrieved from http://www.englandrugby.com/my-rugby/players/player-health/

Salehi, A., Zhang, J. H., & Obenaus, A. (2017, July 1). Response of the cerebral vasculature following traumatic brain injury. *Journal of Cerebral Blood Flow and Metabolism*, Vol. 37, pp. 2320–2339. SAGE Publications Ltd.

Salmon, D. M. (2014). *An Examination of Neck Strength, Endurance, Neck Pain and Neck Stiffness in Rugby Union Players*. Retrieved from University of Otago website: https://ourarchive.otago.ac.nz/handle/10523/4955

Salvatore, J., & Marecek, J. (2010). Gender in the Gym: Evaluation Concerns as Barriers to Women’s Weight Lifting. *Sex Roles*, *63*(7–8), 556–567. Retrieved from https://link.springer.com/article/10.1007/s11199-010-9800-8

Sasaki, K., Sato, H., Nakamura, A., Yamamoto, T., Watanabe, I., Katsuta, T., & Kono, I. (2020). Clarifying the structure of serious head and spine injury in youth Rugby Union players. *PLOS ONE*, *15*(7), e0235035. Retrieved from https://dx.plos.org/10.1371/journal.pone.0235035

Savitsky, B., Givon, A., Rozenfeld, M., Radomislensky, I., & Peleg, K. (2016). Traumatic brain injury: It is all about definition. *Brain Injury*, *30*(10), 1194–1200. Retrieved from https://www.tandfonline.com/doi/full/10.1080/02699052.2016.1187290

Schnebel, B., Gwin, J. T., Anderson, S., & Gatlin, R. (2007). IN VIVO STUDY OF HEAD IMPACTS IN FOOTBALL. *Neurosurgery*, *60*(3), 490–496. Retrieved from https://academic.oup.com/neurosurgery/article/60/3/490/2555116

Simon Kemp, C., & Andy Smith. (2019). England Professional Injury Surveillance Project. In *Medical Advisor, RPA)*. Andy Reynolds.

Six Nations Rugby. (2020a). Six Nations Rugby | England. Retrieved August 15, 2020, from https://www.sixnationsrugby.com/team/england/#squad

Six Nations Rugby. (2020b). Six Nations Rugby | France. Retrieved August 15, 2020, from https://www.sixnationsrugby.com/team/france/#squad

Six Nations Rugby. (2020c). Six Nations Rugby | Ireland. Retrieved August 15, 2020, from https://www.sixnationsrugby.com/team/ireland/#latest

Six Nations Rugby (2020). Six Nations Rugby | Wales. Retrieved August 15, 2020, from https://www.sixnationsrugby.com/team/wales/#squad

Slater, A., & Tiggemann, M. (2010). "Uncool to do sport": A focus group study of adolescent girls' reasons for withdrawing from physical activity. *Psychology of Sport and Exercise*, *11*(6), 619–626.

Slobounov, S. M., Walter, A., Breiter, H. C., Zhu, D. C., Bai, X., Bream, T., … Talavage, T. M. (2017). The effect of repetitive subconcussive collisions on brain integrity in collegiate football players over a single football seasonA multi-modal neuroimaging study. *NeuroImage: Clinical*.

Slobounov, S., Sebastianelli, W., & Hallett, M. (2012). Residual brain dysfunction observed one year post-mild traumatic brain injury: Combined EEG and balance study. *Clinical Neurophysiology*, *123*(9), 1755–1761.

Smith, D. H., & Meaney, D. F. (2000). Axonal Damage in Traumatic Brain Injury. *The Neuroscientist*, *6*(6), 483–495. Retrieved from http://journals.sagepub.com/doi/10.1177/107385840000600611

Smith, E. K. (2017). Changes in Anthropometric and Physiological Characteristics of Male Collegiate Rugby Union Players Throughout a Season (Illinois State University). Retrieved from https://ir.library.illinoisstate.edu/etd/712

Sobue, S., Kawasaki, T., Hasegawa, Y., Shiota, Y., Ota, C., Yoneda, T., … Kaneko, K. (2018). Tackler's head position relative to the ball carrier is highly correlated with head and neck injuries in rugby. *British Journal of Sports Medicine*, *52*(6), 353–358.

Solis-Mencia, C., Ramos-Álvarez, J. J., Murias-Lozano, R., Aramberri, M., & Saló, J. C. (2019). Epidemiology of Injuries Sustained by Elite Under-18 Rugby Players. *Journal of Athletic Training*, *54*(11), 1187–1191.

Sollmann, N., Echlin, P. S., Schultz, V., Viher, P. V., Lyall, A. E., Tripodis, Y., … Koerte, I. K. (2018). Sex differences in white matter alterations following repetitive subconcussive head impacts in collegiate ice hockey players. *NeuroImage: Clinical*, *17*, 642–649.

Solomon, G. (2018, May 19). Chronic traumatic encephalopathy in sports: a historical and narrative review. *Developmental Neuropsychology*, Vol. 43, pp. 279–311. Retrieved from https://www.tandfonline.com/doi/abs/10.1080/87565641.2018.1447575

Sorby-Adams, A. J., Marcoionni, A. M., Dempsey, E. R., Woenig, J. A., & Turner, R.

J. (2017, August 17). The role of neurogenic inflammation in blood-brain barrier disruption and development of cerebral oedema following acute central nervous system (CNS) injury. *International Journal of Molecular Sciences*, Vol. 18. MDPI AG.

Sport Wales. (2013). *School Sport Survey 2013 The State of the Nation*. Retrieved from: http://sportwales.org.uk/media/1195698/state_of_the_nation_october_2013_english.pdf

Sport Wales. (2016). *Calls 4 Action: Women and girls and sport.* Retrievied from: https://www.sport.wales/files/6935f3a174163e0661b49e0016ec5960.pdf

Sports Council for Wales. (2007). PE provision in primary schools. In *Sports Council for Wales Update* (Vol. 60). Retrieved from www.sports-council-wales.org.uk

Sran, M. M., Stotz, P. J., Normandin, S. C., & Robinovitch, S. N. (2010). Age differences in energy absorption in the upper extremity during a descent movement: Implications for arresting a fall. *Journals of Gerontology - Series A Biological Sciences and Medical Sciences*, *65 A*(3), 312–317. Retrieved from /pmc/articles/PMC2822282/?report=abstract

Steinskog, D. J., Tjøtheim, D. B., & Kvamstø, N. G. (2007). A cautionary note on the use of the Kolmogorov-Smirnov test for normality. *Monthly Weather Review*, *135*(3), 1151–1157. Retrieved from http://journals.ametsoc.org/mwr/article-pdf/135/3/1151/4228002/mwr3326_1.pdf

Stemper, B. D., Shah, A. S., Pintar, F. A., McCrea, M., Kurpad, S. N., Glavaski-Joksimovic, A., … Budde, M. D. (2015). Head Rotational Acceleration Characteristics Influence Behavioral and Diffusion Tensor Imaging Outcomes Following Concussion. *Annals of Biomedical Engineering*, *43*(5), 1071–1088.

Stemper, B. D., Yoganandan, N., Pintar, F. A., Maiman, D. J., Meyer, M. A., DeRosia, J., … Paskoff, G. (2008). Anatomical Gender Differences in Cervical Vertebrae of Size-Matched Volunteers. *Spine*, *33*(2), E44–E49. Retrieved from https://insights.ovid.com/crossref?an=00007632-200801150-00025

Sterling, M., Jull, G., Vicenzino, B., Kenardy, J., & Darnell, R. (2003). Development of motor system dysfunction following whiplash injury. *Pain*, *103*(1–2), 65–73.

Stevens, J. A., & Sogolow, E. D. (2005). Gender differences for non-fatal unintentional fall related injuries among older adults. *Injury Prevention*, *11*(2), 115–119. Retrieved from www.injuryprevention.com

Stewart, W., McNamara, P. H., 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. Retrieved from https://academic.oup.com/qjmed/article-lookup/doi/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*.

Streifer, M., Brown, A. M., Porfido, T., Anderson, E. Z., Buckman, J. F., & Esopenko,

C. (2019, March 1). The potential role of the cervical spine in sports-related concussion: Clinical perspectives and considerations for risk reduction. *Journal of Orthopaedic and Sports Physical Therapy*, Vol. 49, pp. 202–208. Movement Science Media.

Sullivan, S. J., Bourne, L., Choie, S., Eastwood, B., Isbister, S., McCrory, P., & Gray, A. (2009). Understanding of Sport Concussion by the Parents of Young Rugby Players: A Pilot Study. *Clinical Journal of Sport Medicine*, *19*(3), 228–230. Retrieved from https://insights.ovid.com/crossref?an=00042752-200905000-00006

Suzuki, K., Nagai, S., Iwai, K., Furukawa, T., Mukai, N., Miyakawa, S., & Takemura, M. (2020a). Characteristics and factors of concussion events for tacklers in collegiate rugby union. *Scandinavian Journal of Medicine & Science in Sports*, *30*(1), 185–192. Retrieved from https://onlinelibrary.wiley.com/doi/abs/10.1111/sms.13553

Suzuki, K., Nagai, S., Iwai, K., Furukawa, T., Mukai, N., Miyakawa, S., & Takemura, M. (2020b). Characteristics and factors of concussion events for tacklers in collegiate rugby union. *Scandinavian Journal of Medicine & Science in Sports*, *30*(1), 185–192. Retrieved from https://onlinelibrary.wiley.com/doi/abs/10.1111/sms.13553

Sye, G., Sullivan, S. J., & McCrory, P. (2006, December). High school rugby players' understanding of concussion and return to play guidelines. *British Journal of Sports Medicine*, Vol. 40, pp. 1003–1004.

Thompson, A. E., Anisimowicz, Y., Miedema, B., Hogg, W., Wodchis, W. P., & Aubrey-Bassler, K. (2016). The influence of gender and other patient characteristics on health care-seeking behaviour: a QUALICOPC study. *BMC Family Practice*, *17*(1), 38. Retrieved from http://bmcfampract.biomedcentral.com/articles/10.1186/s12875-016-0440-0

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

Tjepkema, M. (2008). *Article Health care use among gay, lesbian and bisexual Canadians*. Retrieved from www.statcan.ca

Toronjo-Hornillo, L., DelCastillo-Andrés, Ó., Campos-Mesa, M., Díaz Bernier, V., & Zagalaz Sánchez, M. (2018). Effect of the Safe Fall Programme on Children's Health and Safety: Dealing Proactively with Backward Falls in Physical Education Classes. *Sustainability*, *10*(4), 1168. Retrieved from http://www.mdpi.com/2071-1050/10/4/1168

Tucker, R., Hester, B., Cross, M., Kemp, S., & Raftery, M. (2017a). Tackle technique and body position of the tackler and ball carrier significantly influences head injury risk in rugby union. *British Journal of Sports Medicine, 51*(11), A70.2-A70.

Tucker, R., Hester, B., Cross, M., Kemp, S., & Raftery, M. (2017b). Tackle technique and body position of the tackler and ball carrier significantly influences head injury risk in rugby union. *British Journal of Sports Medicine, 51*(11), A70.2-

A70.

Tucker, R., Raftery, M., Kemp, S., Brown, J., Fuller, G., Hester, B., … Quarrie, K. (2017). Risk factors for head injury events in proffessional rugby union: a video analysis of 464 head injury events to inform proposed injury prevention strategies. *Br J Sports Med, 51,* 1152–1157. Retrieved from http://bjsm.bmj.com/

Turner, J., & LaBella, C. R. (2020). Persistent Post-concussion Symptoms and Long-Term Sequelae. In *Spinal Conditions in the Athlete* (pp. 81–88). Springer International Publishing.

Tyler, R., Mannello, M., Mattingley, R., Roberts, C., Sage, R., Taylor, S. R., … Stratton, G. (2016). Results from Wales' 2016 report card on physical activity for children and youth: Is Wales turning the tide on children's inactivity? *Journal of Physical Activity and Health, 13*(11), S330–S336.

Ultimate Rugby. (2020a). England Women. Retrieved from https://www.ultimaterugby.com/england-womens/squad

Ultimate Rugby. (2020b). France Women. Retrieved from https://www.ultimaterugby.com/france-womens/squad

US Department of Health and Human Services. (2020). Data Chart | Healthy People 2020. Retrieved August 18, 2020, from Healthy People 2020 website: https://www.healthypeople.gov/2020/data/Chart/4863?category=5.1&by=Educational attainment (of mother, 25 years and over)&fips=-1

Vagnozzi, R., Signoretti, S., Cristofori, L., Alessandrini, F., Floris, R., Isgró, E., … Lazzarino, G. (2010). Assessment of metabolic brain damage and recovery following mild traumatic brain injury: A multicentre, proton magnetic resonance spectroscopic study in concussed patients. *Brain*, *133*(11), 3232–3242. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/20736189

Valentini, N. C., Logan, S. W., Spessato, B. C., de Souza, M. S., Pereira, K. G., & Rudisill, M. E. (2016). Fundamental Motor Skills Across Childhood: Age, Sex, and Competence Outcomes of Brazilian Children. *Journal of Motor Learning and Development*, *4*(1), 16–36. Retrieved from https://journals.humankinetics.com/view/journals/jmld/4/1/article-p16.xml

van der Kruk, E., & Reijne, M. M. (2018). Accuracy of human motion capture systems for sport applications; state-of-the-art review. *European Journal of Sport Science*, *18*(6), 806–819. Retrieved from https://www.tandfonline.com/doi/full/10.1080/17461391.2018.1463397

Vasavada, A. N., Danaraj, J., & Siegmund, G. P. (2008). Head and neck anthropometry, vertebral geometry and neck strength in height-matched men and women. *Journal of Biomechanics*, *41*(1), 114–121.

Walker, K. R., & Tesco, G. (2013). Molecular mechanisms of cognitive dysfunction following traumatic brain injury. *Frontiers in Aging Neuroscience*, Vol. 5.

Welch, V., Doull, M., Yoganathan, M., Jull, J., Boscoe, M., Coen, S. E., … Tudiver, S. (2017). Reporting of sex and gender in randomized controlled trials in Canada: a cross-sectional methods study. *Research Integrity and Peer Review*, *2*(1), 1–11. Retrieved from https://link.springer.com/articles/10.1186/s41073-017-0039-6

Welsh Rugby Union. (2020). Women’s Squad. Retrieved from https://www.wru.wales/fixtures-and-teams/teams/wales-women/

Winkler, E. A., Minter, D., Yue, J. K., & Manley, G. T. (2016, October 1). Cerebral Edema in Traumatic Brain Injury: Pathophysiology and Prospective Therapeutic Targets. *Neurosurgery Clinics of North America*, Vol. 27, pp. 473–488. W.B. Saunders.

World Rugby. (2014). World Rugby Player Welfare - Putting Players First : Weight consideration guideline. Retrieved August 5, 2020, from Research and Expert Papers website: http://playerwelfare.worldrugby.org/?subsection=64

World Rugby. (2017). Player Numbers | World Rugby. Retrieved September 15, 2020, from https://www.world.rugby/development/player-numbers?lang=en

World Rugby. (2019a). Rugby Ready - World Rugby’s preparation resource : The tackle. Retrieved January 17, 2020, from https://rugbyready.worldrugby.org/?section=65&tab=tab-2

World Rugby. (2019b). World Rugby Launch Women’s Campaign. Retrieved August 16, 2020, from https://www.englandrugby.com/news/article/world-rugby-launch-womens-campaign

World Rugby. (2019c). World Rugby Player Welfare - Putting Players First. Retrieved April 23, 2020, from https://playerwelfare.worldrugby.org/concussion

World Rugby. (2019d). World Rugby Recognise and Remove concussion education completed by record numbers | www.world.rugby. Retrieved July 30, 2020, from https://www.world.rugby/news/134498?lang=en

World Rugby. (2020a). World Rugby Laws - World Rugby’s Law Education Web Site: Law 15: Ruck. Retrieved January 16, 2020, from World Rugby Laws website: https://laws.worldrugby.org/?law=15&language=EN

World Rugby. (2020b, May 31). Women’s Rankings | World Rugby. Retrieved September 17, 2020, from https://www.world.rugby/rankings/wru

Wu, L. C., Nangia, V., Bui, K., Hammoor, B., Kurt, M., Hernandez, F., … Camarillo, D. B. (2016). In Vivo Evaluation of Wearable Head Impact Sensors. *Annals of Biomedical Engineering*, *44*(4), 1234–1245. Retrieved from /pmc/articles/PMC4761340/?report=abstract

Yoganandan, N., Bass, C. R., Voo, L., & Pintar, F. A. (2017). Male and Female Cervical Spine Biomechanics and Anatomy: Implication for Scaling Injury Criteria. *Journal of Biomechanical Engineering*, *139*(5), 1–5.

Yuen, T. J., Browne, K. D., Iwata, A., & Smith, D. H. (2009). Sodium channelopathy induced by mild axonal trauma worsens outcome after a repeat injury. *Journal of Neuroscience Research*, *87*(16), 3620–3625. Retrieved from https://pubmed.ncbi.nlm.nih.gov/19565655/

Zhang, A. L., Sing, D. C., Rugg, C. M., Feeley, B. T., & Senter, C. (2016). The Rise of Concussions in the Adolescent Population. *Orthopaedic Journal of Sports Medicine*, *4*(8), 2325967116662458. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/27579334

Zuckerman, S. L., Kerr, Z. Y., Yengo-Kahn, A., Wasserman, E., Covassin, T., & Solomon, G. S. (2015). Epidemiology of Sports-Related Concussion in NCAA Athletes From 2009-2010 to 2013-2014. *The American Journal of Sports Medicine*, *43*(11), 2654–2662. Retrieved from http://journals.sagepub.com/doi/10.1177/0363546515599634

Zwolski, C., Quatman-Yates, C., & Paterno, M. V. (2017). Resistance Training in Youth: Laying the Foundation for Injury Prevention and Physical Literacy. *Sports Health: A Multidisciplinary Approach*, *9*(5), 436–443. Retrieved from http://journals.sagepub.com/doi/10.1177/1941738117704153

Appendix

Appendix A

British Universities and Colleges Sport (BUCS) men and women's premier division winning margins data. This data was published on the BUCS android application accessed 20/05/2020.

Women's	Cardiff	Cambridge	Bristol	Oxford	Swansea	Sussex
Cardiff	X	5	3	9	34	57
Cambridge	10	X	0	18	39	57
Bristol	26	18	X	0	2	28
Oxford	30	11	46	X	26	19
Swansea	39	11	54	/	X	27
Sussex	39	63	61	26	15	X

Men's	Hartpury	Bristol	Exeter	Cardiff	St Mary's	Cardiff Met	Bath
Hartpury	X	11	11	35	2	6	64
Bristol	6	X	14	16	30	33	5
Exeter	5	6	X	3	18	3	42
Cardiff	20	2	21	X	18	3	21
St Mary's	23	6	11	14	X	4	12
Cardiff Met	25	9	27	20	5	X	46
Bath	57	18	8	26	1	5	X