An investigation into mild traumatic brain injury identification, management, and mitigation.

Edward Daly

A thesis submitted in partial fulfilment of the requirements of

Oxford Brookes University for the degree of Doctor of Philosophy.

Centre for Movement, Occupational and Rehabilitation Sciences (MOReS)

Oxford Brookes Centre for Nutrition and Health (OxBCNH)

Department of Sport, Health Sciences and Social Work

Faculty of Health and Life Sciences

Oxford Brookes University

June 2023

Abstract

Concussion is classified as a mild traumatic brain injury which can be induced by biomechanical forces such as a physical impact to the head or body, which results in a transient neurological disturbance without obvious structural brain damage. Immediate access to tools that can identify, diagnosis and manage concussion are wide ranging and can lack consistency in application. It is well documented that there are frequent incidences of concussion across amateur and professional sport such as popular contact sports like rugby union.

A primary aim of this thesis was to establish the current modalities of 'pitch side' concussion management, identification, and diagnosis across amateur and professional sporting populations. Furthermore, the research sought to understand existing concussion management and concussion experiences by means of recording the player's experiences and perceptions (retired professional rugby union players). These qualitative studies sought to gain insights into concussion experiences, the language used to discuss concussion and the duty of care which medical staff, coaching personnel, and club owners have towards professional rugby players in their employment.

In addition, possible interventions to reduce the incidence of concussion in amateur and professional sports were investigated. These included a 'proof of concept' using inertial measurement units and a smartphone application, a tackle technique coaching app for amateur sports. Other research data investigating the use of neurological function data and neuromuscular fatigue in current professional rugby players as a novel means of monitoring injury risk were included in this research theme.

The findings of these studies suggest that there is an established head injury assessment process for professional sports. However, in amateur sport settings, this is not the existing practice and may expose amateur players to an increased risk of post-concussion syndrome or early retirement. Many past professional rugby union players stated that they did not know the effects of cumulative repetitive head impacts. They discussed how they minimised and ignored repeated concussions due to peer pressure or pressure from coaches or their own internal pressures of maintaining a livelihood. These data suggest that players believed that strong willed medical staff, immutable to pressures from coaching staff or even athletes themselves, were essential for player welfare and that club owners have a long-term duty of care to retired professional rugby union players. However, there are anecdotal methods suggested to reduce concussion incidence. For example, neck strengthening techniques to mitigate against collision impacts. There is, no longitudinal evidence to suggest that neck strength can reduce the impacts of concussion in adult populations . Additionally, other factors such as lowering the tackle height in the professional and amateur game is currently being investigated as a mitigating factor to reduce head injury risk.

The final theme of the thesis investigated possible methods to reduce injury incidence in amateur and professional athletes. The novel tackle technique platform could assist inexperienced amateur coaches on how to coach effective tackle technique to youth players. The findings from the neurological function data suggests that this may be an alternative way for coaches to assess and gather fatigue data on professional rugby union players alongside additional subjective measures and neuromuscular function data. Recently, the awareness of concussion as an injury and the recognition of concussion in many sports settings has improved. These incremental improvements have led to increased discussion regarding possible measures to mitigate the effects of concussion. There are many additional procedures to be implemented before a comprehensive concussion management is universally available, particularly in amateur and community sports. These necessary processes could be technological advances (e.g., using smart phone technology) for parents and amateur coaches to assist in the early identification of concussion or evidence-based concussion reduction strategies.

Statement of Authorship

Except where reference is made in the text of the thesis, this thesis contains no material published elsewhere or extracted in whole or in part from a thesis accepted for the award of any other degree or diploma. No other person's work has been used without due acknowledgment in the main text of the thesis. This thesis has not been submitted for the award of any degree or diploma in any other tertiary institution. The research ethics committee of Atlantic Technological University approved all methods, and participants gave signed and/or verbal informed consent prior to data collection.

Edward Daly

COVID-19 Impact Statement

The original intention of this research was to conduct additional data sampling in the field with participants from this industry. Unfortunately, due to COVID-19 restrictions, many of the professional and amateur rugby teams we had intended to work with were closed for substantial periods (2020/2021) of time during the implementation of these studies. This resulted in a smaller number of participants being recruited than initially intended in certain studies.

Publications Relevant to Thesis

Publications

Chapter 2 - Daly, E., Pearce, A. J., Finnegan, E., Cooney, C., McDonagh, M., Scully, G., ... & Ryan, L. (2022). An assessment of current concussion identification and diagnosis methods in sports settings: a systematic review. *BMC sports science, medicine and rehabilitation, 14(1), 1-10.*https://doi.org/10.1186/s13102-022-00514-1

Chapter 3 - Daly, E., Pearce, A. J., & Ryan, L. (2021). A systematic review of strength and conditioning protocols for improving neck strength and reducing concussion incidence and impact injury risk in collision sports; is there evidence? *Journal of functional morphology and kinesiology, 6(1), 8*.https://doi.org/10.3390/jfmk6010008

Chapter 4 - **Daly, E**., White, A., Blackett, A. D., & Ryan, L. (2021). Pressure. A qualitative analysis of the perception of concussion and injury risk in retired professional rugby players. *Journal of functional morphology and kinesiology, 6(3), 78.*https://doi.org/10.3390/jfmk6030078

Chapter 5 - **Daly, E.,** Pearce, A. J., Blackett, A. D., & Ryan, L. (2022). Facing the consequences of concussion; a qualitative and thematic analysis of interviews with ex-professional rugby player. *J. Sport Exerc. Sci.(NZ), 6, 22-30*.https://doi.org/10.36905/jses.2022.01.04

Chapter 6 - **Daly, E**., Blackett, A. D., Pearce, A. J., & Ryan, L. (2022). Protect the player, protect the game: reflections from ex-professional rugby union players on law changes, protective equipment, and duty of care in the professional game. *Journal of functional morphology and kinesiology, 7(4), 91*.https://doi.org/10.3390/jfmk7040091

Chapter 7 - Daly, E., Pearce, A. J., Esser, P., & Ryan, L. (2022). Evaluating the relationship between neurological function, neuromuscular fatigue, and subjective performance measures in professional rugby union players. *Frontiers in Sports and Active Living, 4, 438*.https://doi.org/10.3389/fspor.2022.1058326

Chapter 8 - Daly, E., Esser, P., Griffin, A., Costello, D., Servis, J., Gallagher, D., & Ryan, L. (2022). Development of a Novel Coaching Platform to Improve Tackle Technique in Youth Rugby Players: A Proof of Concept. *Sensors, 22(9), 3315.*https://doi.org/10.3390/s22093315

Conference Presentations

Conaghan, C., **Daly, E**., Ryan, L, Pearce, A., (2022) Effects of educational interventions on knowledge and attitudes towards concussion: a systematic review. (Abstract / Poster) 6th International Consensus Conference on Concussion in Sport, Amsterdam.

Daly, E., Ryan, L, Pearce, A., (2022) Neck strength evaluation and injury risk reduction: a systematic review. (Abstract / Poster) 6th International Consensus Conference on Concussion in Sport, Amsterdam.

Heads Up! Concussion in Sport Conference (March 2022, ATU, Ireland)

Acknowledgments

Firstly, I would like to thank my supervisory team Dr Patrick Esser, Dr Lisa Ryan and Professor Alan Pearce who have offered their vast experience, knowledge, and patience over the last three and half years. It has been an absolute honour and privilege to work with them. The ongoing motivation they provided along with an overall sense of positivity made it a thoroughly rewarding and life changing experience.

The learning experiences and research skills that I have gained were made possible by working with a vast array of people. With respect to this, I would like to acknowledge the support of Atlantic Technological University (ATU) and the staff development team who were a constant support throughout the process. While writing chapters of the thesis, I was a member of the Erasmus + concussion education project in ATU, this work exposed me to many collaborators and opportunities across Europe, the USA and Australia. The project generated many challenges but in general, the knowledge and insights gained have certainly influenced my future research goals. In particular, I'd like to thank and acknowledge the ATU members of the Erasmus + project team.

Many of the chapters in the thesis took a novel investigative approach, with respect to this I would like to recognise the cooperation of Connacht Rugby and the Irish Rugby Football Union for their assistance. Furthermore, I would like to thank the coaches and players of Connacht Rugby who enabled me to gather longitudinal data during a very competitive and cluttered playing schedule. The qualitative components of the thesis were challenging and humbling in many respects, primarily due to the accounts of injury, both physical and neurological as recounted by the retired players. I'd like to sincerely thank and offer my gratitude to these players who shared their experiences. Some have experienced life changing injuries; others retired unscathed, and a further cohort don't know what lies in store for their long-term health. I hope they took something from the interviews and discussions about their careers. I hope they continue to share their insights about how their injuries were managed during their careers, so that we can make the game of rugby union safer for future generations.

I'd like to thank the Computer Science Department in ATU for their time, support, and commitment to translating a concept into a tangible application. They were generous with their time, knowledge and understanding to assist a non-computer engineer attempt to convert technical rugby competencies to computer code. My final and deepest thanks go to my research partner (and wife), Dr Lisa Ryan, without her ongoing encouragement, advice, belief and support, this thesis would not have been possible.

Contents

Abbreviations

AU – Arbitrary units

BESS – Balance error scoring system

CMJ – Countermovement jump

CNS – Central nervous system

CTE – Chronic traumatic encephalopathy

DC – Direct current

DF – Degrees of freedom

ECG – Electrical heart activity

fMRI – Functional magnetic resonance imaging

GCS – Glasgow coma scale

GI – Gait Initiation

GT – Gait Termination

HIA – Head injury assessment

HRV – Heart rate variability

ImPACT - Immediate post-concussion and cognitive testing

IMU – Inertial measurement unit

KD – King Devick

mBESS – modified balance error scoring system

miRNA – Micro ribonucleic acid

MotCoTe – Motor Cognitive Test Battery

MRI – Magnetic resonance imaging

mTBI – Mild traumatic brain injury

MULES – Mobile Universal Lexicon Evaluation System

OW – Omegawave

PCS – Prospective cohort study

PCSS – Post concussion symptom scale

POMS – Profile of mood state

PSCA – Pitch side concussion assessment

RCS – Retrospective cohort study

RSImod – Reactive strength index modified

RTP – Return to play

SAC – Standardized assessment of concussion

SCAT3 - Sport concussion assessment tool 3

SCAT5 – Sport concussion assessment tool 5

SOT – Sensory organisation

SRC – Sports related concussion

TG – Tandem gait

TMS – Transcranial magnetic stimulation

VA – Video analysis

VOMS – Vestibular ocular motor screening

List of Tables

List of Figures

Chapter 1 – Introduction

1.1 What is a concussion.

A concussion is classified as a mild traumatic brain injury (mTBI) which can be induced by biomechanical forces such as a physical impact to the head or body, which results in a transient neurological disturbance without obvious structural brain damage (Blumbergs et al. 1994). A concussion can be classified using the Glasgow Coma Scale (GCS) scoring system which ranges from mild to severe depending on the level of consciousness that is evident (a mild GCS score of 13–15; moderate, GCS score of 9–12; and severe in those with a GCS score < 8) (Sussman et al. 2018). The symptomology linked to the injury can include headaches, amnesia, difficulty concentrating, nausea, poor concentration, vestibular complications and insomnia (Harriss et al. 2020). Documented cases of concussion have been intrinsically linked to many sports such as boxing since the early part of the 20th century (Mc Kee et al. 2009). Martland (1929) first used the phrase 'punch drunk' (the title of his paper) to describe the syndrome. In his 1928 paper, Martland describes microscopic cerebral haemorrhages while carrying out autopsies of boxers (n=309) who were exposed to repetitive head trauma during their careers (Martland and Beling, 1929) .

1.1.2 Long term risks of concussion and repetitive brain trauma in sports

The current prevalence of concussion in sports such as rugby union remains a research topic in the 21st century (Di Pietro et al. 2021). One reason is the emerging evidence of the links between concussion, and repetitive head trauma seen in contact and collision sports, further to combat sports. A study by Suter et al. (2022) reported recorded cases of chronic traumatic encephalopathy (CTE) in ex-professional rugby league, amateur rugby league and Australian rules football players related to their careers in their sport. CTE is a degenerative brain disease that is commonly found in people who have experienced repeated impacts to the head which results in symptoms such as loss in impulse control, aggression, and progressive dementia (VanItallie, 2019). The high risk of long-term cognitive dysfunction because of repetitive head impacts is not exclusive to professional sports. For example, McAllister et al. (2017) reported that amateur athletes who experienced concussive or -sub-concussive events (i.e., an event which does not cause symptoms) were at a higher risk of being exposed to neurocognitive issues later in life. In a recent publication by (Suter et al. 2022) retrospectively examining brain samples (n=180) in a hospital neuropathology practice, this hypothesis of neurocognitive events was escalated as this study documented cases of CTE in amateur male athletes (n=4). There are many incidences where participants in sports choose not to disclose or conceal a concussion (Doucette et al. 2021, Walshe et al. 2022). This has created a notable issue regarding the reported number of concussions that occur in either professional or amateur sports, for example peer pressure or excessive pressures from coaching staff to compete (Conway et al., 2020; Longworth et al. 2021). The phenomena of either under-reporting or not reporting will persist in sports without adequate evidence-based interventions. Data from recent estimates of incidences of under reporting suggest that between 30.5% and 78.3% of participants continued to play sports while experiencing concussive symptoms (Kroshus et al. 2017). This issue is not restricted exclusively to male participants as it is equally evident in female sports. For example, Sanderson et al. (2017) reported that female athletes refrained from reporting concussive symptoms in their chosen sport. It is now widely accepted that females may be more susceptible to concussion and can take longer for symptoms to resolve when compared to males (Mc Groarty et al. 2020). The rationale for why concussion in female sports presents differently is not clearly understood. However, there is evidence to suggest that structural differences between the male and female brains may be a factor (Solomito et al. 2019). Other theories suggest that the mechanism of how concussions are experienced may be a factor. Most concussions in males tend to occur with contact with an opposing player, whereas most female concussions tended to occur with impacts on the playing surface (Merritt et al. 2019, Sundaram et al. 2022) Research will support the view that female participants experience concussion symptomology in a different manner and may take longer to recover fully from the injury (Desai et al. 2019; Davis-Hayes et al. 2017).

With respect to these circumstances, it is evident that concussion as an injury has been a prominent factor in many well-known sports (e.g., American Football, Australian rules football, rugby union, association football (soccer), and rugby league) for a prolonged period. Knowledge of the injury is still evolving, and a significant knowledge gap remains in the understanding of concussion and the management of concussion on a broader scale in male and female populations.

1.2 The influence of professional sport on community sport

Amateur rugby union has been influenced by many practices which originated in the professional game such as workload management, current coaching practices and updated strength training protocols (Zabaloy et al. 2022, Griffin et al. 2021). Similarly, the recording of injury incidence data has established that concussion occurs across many levels of sport, whether these sports are professional or amateur. Although injury surveillance began in professional rugby union, the Professional Rugby Injury Surveillance Project (PRISP) was commenced in 2002. The practice is becoming more prevalent in amateur levels of the game to record concussion incidence, for example the Irish Rugby Injury Surveillance Project began in 2016.

The fundamentals of concussion management are early identification and access to appropriate treatment (Arbogast et al. 2017). Delays in concussion identification can impinge on the recovery process and increase future risk of concussion and other subsequent injuries associated with the initial concussive injury due to deficits in neuromuscular control (Howell et al. 2018).

In professional rugby union, early identification and removal from activity are of paramount importance for professional athletes (Echemendia et al. 2023). However, there is a paucity of research on the prevalence, characteristics and management behaviour relating to concussion in community sports (amateur or recreational sports) (Clacy et al. 2019). As most research in concussion is focused on elite sports (primarily elite male sports), it is difficult to compare these research outcomes to concussions in community or amateur sports (Melo et al. 2018).

Most amateur (community) sports do not have access to suitably qualified medical personnel during training sessions or competitions (Clacy et al. 2019). This means that the responsibility of managing potential concussive events frequently resides with match officials (referees), amateur volunteer coaches, parents, and on some occasions, teammates. Addressing the current lack of knowledge and education related to the mechanisms, duration, awareness, treatment, and complexity of concussions is essential in community sports (Clacy et al. 2019).

Community amateur level sports organisations are beginning to engage in recording injury rates in their sport. A report by Acquired Brain Injury (Ireland) and the Gaelic Players Association (GPA) in 2012, recorded that 54% of amateur players surveyed said that they have sustained a concussion while playing. Most respondents reported that they had sustained two to five concussions in their athletic career and one-in-four participants continued to play while knowingly concussed, 42% of which did not remember the remainder of the game. A study by Sullivan et al. (2017) reported that males were significantly more likely to play while concussed than females (40.9% and 17.2%, respectively). This study indicated that participants lacked a full understanding of concussion, and common misconceptions about concussion prevailed. Many studies have indicated that a concussion education gap exists and that amateur athletes were willing to continue to display unsafe behaviours by continuing to participate (Viljoen et al. 2017; O'Connor et al. 2020). In the context of amateur sports, it is appropriate to state that even where training and advice have been provided about concussion, certain cohorts of amateur athletes choose to disregard the guidance that is available (Leahy et al. 2020; Sullivan et al. 2017).

Currently, there is a scarcity of follow-up research on concussions amongst amateur community-level athletes. The lack of research is concerning, firstly, based on participation levels alone, the largest group of 'at-risk athletes' exist in amateur community-level sports. For example, in the United Kingdom, it is estimated that 44.7% of children aged between 11 -15 years participate in soccer, along with 31.4% of children aged 5-10 years old engaging in soccer regularly (Statista.com). Participation rates in amateur sports in Ireland are equally high. Based on club membership, the most popular participation sports such as Gaelic football, hurling and camogie have active playing members of more than 367,000 registered players along with over 2,000 affiliated amateur clubs (National Planning Framework, Gaelic Athletic Association, 2017).). The participation numbers for rugby union worldwide suggest that the sport has in excess of 9.6 million players globally including 2.7 million female participants (World Rugby, 2018). With such high volumes of participants involved in amateur sports coupled with the lack of visibility of true incidence rates, there is a burgeoning need for follow-up research.

1.3 Cumulative effects of concussion in amateur community sport

Even though concussion is considered a transient neurological event, research suggests that the time it takes to make a full recovery from a concussion can vary considerably. A study by D'Lauro et al. (2018) found that the gender of participants affected the length of time it took to return-to-activity. In this study, males reported a significantly shorter return to play (24.7 days) when compared to female participants (35.5 days). The current evidence suggests that long-term issues like depression are thought to be associated with multiple concussions or sub-concussive impacts (Yrondi et al. 2017). However, as this is an evolving area of research, the consequences of repeated incidences of concussion in amateur sports have been noted. A study by Schlegel et al. (2021) on amateur mixed martial artists recorded that, athletes can recover fully from a single concussion. The study went on to report that health concerns arose, after repeated concussions. Demonstrating that there could be potential for the development of neurodegenerative disorders over the long term, which could predispose amateur participants to CTE or developing CTE because of participating in amateur sport (Schlegel et al. 2021; Pearce et al. 2014, Suter et al. 2021).

This perspective of long-term health is supported by another study (Levitch et al. 2018), where the data suggested that there was evidence to demonstrate the cumulative effects of repetitive head impacts in female amateur soccer players. The evidence for this assertion was that the female participants displayed poorer neurological function after prolonged periods of heading a football (over two weeks) or were involved in the long-term heading of a football (over the previous twelve-month period). Additional research suggests that the cumulative effects of a career playing rugby (professional and amateur) can expose players to long term physical and cognitive issues (Hind et al. 2020, Hind et al. 2021).

These incidences of long-term issues in amateur sport are better understood in professional sports. In a comparison with professional football, a study by Mackay et al. (2019) detected more significant issues in professional male soccer players, where mortality associated with neurological disease was either the primary cause of death or contributed to the cause of death The research by Mackay et al.

(2019) and Russell et al. (2022) has highlighted that there is evidence of a connection between exposure to repeated head impacts and neurodegenerative disease when players advance in age.

As mentioned previously, the key to amateur sports is early identification and management of concussions in amateur settings. Recent research has found that cohorts involving youth populations that have been concussed responded more positively when treated earlier. Those cohorts who were exposed to early clinical care after experiencing a concussion were less likely to have prolonged symptoms and/or recovery times than those that seek treatment at a later stage (Gagnon, 2019). In this respect, enhanced concussion identification modalities must be used in amateur community sports. At present, there is an absence of or inconsistency in suitably qualified medical personnel present at amateur community sports events (Kroshus, 2017). Recently there has been an increased level of research in concussion recognition and management across paediatric and adult populations (Davis et al. 2017; Van Ierssel et al. 2021). With the advent of concussion tracker mobile applications on smart phones, the landscape is changing at the amateur level. The main shortcoming of using advanced diagnostic equipment may be that it may be widely inaccessible to amateur sports populations due to the cost (expensive test equipment) or being used solely in a research setting. Research efforts must be advanced to enhance the availability of concussion reduction or concussion detection modalities in amateur community-level sports.

1.3.1 Overview of accessible concussion detection modalities

Sensor technology (e.g., inertial measurement units [IMUs] can measure rotational forces on the head using a three-dimensional accelerometer and gyroscope. In tandem with information recorded from each head impact, data can be gathered during training or over a season and over multiple seasons to build an impact profile for participants (O'Connor et al. 2017). The use of IMUs has been well-established for the detection of human movement in sporting contexts. A study by Ghattas et al. (2021) further supports this assertion but the overall concept requires further investigation and enhancement.

An alternative option is the use of custom-fitted gumshield sensors, which can provide directional measures for acceleration forces. These types of oral protection have been utilised to measure head impacts only and are not able to detect concussive events in individual athletes. In this respect, gumshields that have sensor technology embedded may have applications when the data generated is compared to video footage in a retrospective manner (Kuo et al. 2018). A further possible application for the use of mouthguards may be in workload management in conjunction using biosignal or biomechanical impact force measurements that can be recorded (Seshadri et al. 2019).

1.4 Advanced methods – neuroimaging and biomarkers

Recent investigations have posited the use of advanced neuroimaging as an emerging research modality for concussion detection and management in sports (King et al. 2019). Standard methods such as routine clinical magnetic resonance imaging (MRI) technology are ineffective in detecting brain injuries that show bleeding on the brain or skull fractures caused by impact (Rizkalla et al. 2021). This is because MRIs measure the structure of the brain and changes to brain structure during an injury. Whereas established technology like functional magnetic resonance imaging (fMRI) can measure brain activity that occurs in different regions of the brain by detecting an increase in blood flow to regions of increased neural activity (Churchill et al. 2020).

The usefulness of fMRI technology is community athletes has further applications in terms of concussion detection and management. A review by Hellewell et al. (2021) has suggested that repeated exposure to head impacts can possibly prolong recovery and associated symptomology from concussion. The authors state that to date, concussion has been mainly studied in male populations. As the consequence, concussion in females has emerged as an important topic due to an increase in female participation in collision sports and gender-based differences in symptomology, and recovery (Hellewell et al. 2021, Walshe et al. 2022). Another recognised technology is transcranial magnetic stimulation (TMS) which utilizes evoked potentials to aid in understanding the pathophysiology of concussion (Pearce et al. 2020). TMS provides data on dysfunction in brain physiology and may be useful as a method to diagnosis and monitor concussion recovery or subconcussive impacts (Pearce et al. 2018, De Virgilio et al. 2019).

In addition to the aforementioned technologies, a further suggested modality of concussion detection is blood biomarker technology. Although this is not a new area of research, there are now emerging protein biomarkers of injury to structures within the brain that can be detected in blood samples (Meier et al. 2020). The research to date suggests that there are still no fully accepted biomarkers to monitor recovery following a concussion injury. An alternative to protein biomarkers in detecting concussion is the search for micro-ribonucleic acids (miRNAs) that control gene expression in human and rodent models (Mitra et al. 2017; Hicks et al., 2020; Wang et al. 2020).

1.5 Multimodal concussion assessment in community settings

As previously mentioned, many of these detection modalities require further development and/or are inaccessible to community sports participants for reasons such as the expense associated with the technology or being used predominantly in research settings. The need to objectively reduce concussion incidence, detect and manage concussions thoroughly, as well as return-to-play decisions will require multimodal solutions in community settings.

To add to this complication, the diagnosis of concussion has been influenced by the array of different concussion injury presentations along with a broad symptom-based assessment criterion. Many researchers now agree that there is an ongoing need for multimodal concussion detection and assessment to comprehensively capture the complex nature of concussion (Howell et al.2021, Sherry et al. 2021). This multimodal approach could be applied to monitoring the recovery of concussion incidence in community settings (Jacquin et al. 2018).

It is well-documented that professional sports have access state of the art technology for diagnosing suspected concussions. This means that professional athletes have access to extensive sports performance teams (e.g., doctors, physiotherapists, rehab specialists, neurologists etc.) to assist decision-making related to the medical status of injured athletes. This is generally not the situation in amateur sports, hence the necessity to develop accessible technology-based solutions for concussion incidence reduction, concussion identification and management for amateur athletes. Frequently the core issue in detecting concussions in amateur sports is that people fail to recognise a concussion or fail to associate amateur sport and concussions. By extension, many concussions remain under-diagnosed or undisclosed in community settings (Leahy et al.2020). Improved concussion assessment is particularly important for 'return-to-play' (RTP),return-to-work or return to school decision-making in sports medicine. Evidence suggests that structural and functional brain abnormalities in males and females may persist even after symptoms have abated (Di Battista et al. 2020). While this phenomenon is not fully understood, it has been suggested that additional injuries during a period of recovery may increase brain vulnerability and prolong the eventual recovery (Terwilliger et al. 2016).

As mentioned previously, amateur or community sports do not have the same access to performance and support teams as professional sports. Currently, many side-line tests in elite sports use the Sports Concussion Assessment Tool 5 (SCAT5) a cognitive concussion assessment tool, the SCAT5 can only be administered by medical professionals (Rosenbloom et al. 2021). This suggests that suitably tailored tools for non-medically trained personnel need to be developed for community sports organisations. If these tools can be formatted for digital platforms to guide non-medical personnel through digital guidelines to 'recognise & remove' participants suspected of experiencing a concussion, these may prove highly useful in community settings.

As stated previously, concussion does not happen in isolation, it needs to be recognised, understood, and treated with care by the person who has endured the trauma. The current issue of non-diagnosed and/or unrecognised concussions has repercussions for private, social, education and work lives of community sports participants. In a broader context, future research could examine data collection methods in community sports context that could assist in the broader health spectrum. For example, monitoring head injury volumes entering hospital admissions to determine the number being admitted with suspected sports concussions could have additional benefits. This data collection could result in concussion passports for community sports which would support traceability and long-term tracking.

Another possible strand of future research would be to determine the use of vestibular/ocular-motor screening (VOMS) technology in concussion diagnosis in community settings (Zahid et al. 2020). Access to cost effective alternative self-monitoring modalities such as balance trackers (e.g., *SWAY*) or disturbances to brainwave activity (*Omegawave*, Espoo, Finland) may prove to be useful in concussion recovery and management at amateur and professional levels.

Premature return to play after concussion may have debilitating or longer-term consequences. It is now widely accepted that visual function is an important component in the post-concussion evaluation (males & females) to identify deficits that may allow for earlier specialist referral (Moran et al. 2019). As a means of possible injury reduction in community settings, particularly in rugby, is the area of tackle safety (Raftery et al. 2021). Across many areas of contact sports like community rugby, the ability to execute safe tackle techniques may assist in alleviating the burden of tackle-related injury. Community coaches must know what good technique looks like and how this can be regressed/progressed in a consistent manner (den Hollander et al. 2021; Hendricks et al. 2020). Tackle technique is a skill that players could practice using safe practise little to ensure players that players are developing safe techniques in a controlled environment. Central to these objectives is to provide effective and accessible concussion identification, management, and mitigating tools (incidence reduction) to participants in community sports.

Chapter2 – Systematic Literature review; current head injury assessment protocols

Preamble

The first study of this PhD aimed to establish the state of the art in terms of concussion assessment tools that are utilised across all sports. The context of this systematic literature review sought to ascertain what was being used as pitch-side assessment in amateur and elite sports. The use of head injury assessments (HIA) although not used across all elite sports is a widespread practice. The HIA seeks to determine whether a player is in a fit state to return to play after a suspected concussion has occurred. In elite sports, there is a multitude of mechanisms available (e.g., an independent physician, team medics, independent match officials). This is generally not the case in amateur sports, whereby many teams do not have access to suitably trained medical staff to determine whether a player should be removed from play. As concussion can be subtle and complex simultaneously, the primary action for amateur sports must be 'recognise and remove'. This review sought to set the groundwork for determining if there are tools available for coaches (amateur and elite), medics (involved in elite sport and amateur sport) and athletes (amateur and elite) to identify concussions in sports settings.

Publication citation:

Daly E, Pearce AJ, Finnegan E, Cooney C, McDonagh M, Scully G, McCann M, Doherty R, White A, Phelan S, Howarth N and Ryan, L. An assessment of current concussion identification and diagnosis methods in sports settings: a systematic review. *BMC Sports Science, Medicine and Rehabilitation. 2022 Dec;14(1):1-0*. https://doi.org/10.1186/s13102-022-00514-1

2.1 Introduction

Despite consensus on the clinical definition of concussion in sports, its immediate and accurate recognition in a clinical setting/pitch side setting remains a challenge to implement beyond the elite level of sport. Currently, only a licensed medical practitioner is entitled to diagnose a concussion (Mc Crory et al. 2017). However, even at the elite level, clinical decision-making is guided on subjective athlete self-reports with the observation of symptoms and severity (Mc Crory et al. 2017). Further, the determination of when an athlete is appropriately ready to return to sport is limited also by subjective symptom scores and imperfect clinical and neuropsychological testing (Kamins et al. 2017). Despite these challenges, the consensus remains a medical decision based upon the resolution of symptoms, as reported by the athlete, as well as completing the return to sport guideline protocols (Mc Crory et al. 2017).

It is important to accurately diagnose a concussion and have the athlete complete a full recovery. It is well described that sustaining a concussion increases the likelihood of incurring a subsequent injury by approximately two-fold (Nordström et al. 2014; Mc Pherson et al. 2019). While epidemiological studies only describe the risk, observational studies have suggested that increased risk appears to be due to continuing neurological and neuromuscular impairments post-concussion (Howell et al. 2018, Wilkerson et al 2017, Scott et al 2020). It has been suggested that experiencing numerous concussions, or exposure to repetitive sub-concussive head trauma, could be associated with long-term consequences such as persistent post concussive symptoms (Pearce et al. 2019) or increasing risk of neurodegenerative disorders such as chronic traumatic encephalopathy, Alzheimer's disease, Parkinson's disease, and motor neuron disease (Livingston et al. 2020, Mez et al. 2017, Suter et al. 2022, Delic et al. 2020, Rubenstein, 2018).

Given these risks, athletes suspected of concussion following an impact must be assessed and identified via the removal of participants for further evaluation and, if diagnosed with concussion, consequently engaged in a graduated return to play protocol (Mc Crory et al. 2017). At the elite levels of competitions, the use of head injury assessment (HIA) tools, such as the Sports Concussion Assessment Tool (SCAT) have been evolving since the first consensus statement published in 2001 (Aubry et al. 2002). While these assessment tools do not replace the medical decision, their use certainly assists the medical practitioner with clinical decision making as well as guidance for return to play clinical decisions for athletes' post-concussion. Previous systematic literature reviews have evaluated the sensitivity of side-line screening tools and assessment protocols (Echemendia et al. 2017, Swart et al. 2021, Patricios et al. 2017). To date no systematic review has evaluated the overall efficacy of these tools and protocols in a field setting. Moreover, it is unknown if HIAs are utilized in non-elite environments, such as amateur club competitions. This systematic review and qualitative analysis aimed to investigate the prevalence and type of current off-field or 'sideline' recognition of suspected concussions. The primary objective was to investigate existing screening and diagnostic tools that are used in identifying concussion, or head injury assessment protocols that are currently used in professional, semi-professional and amateur (club) sports settings.

2.2 Methods

2.2.1 Study design

The review protocol was prospectively registered in the PROSPERO database for systematic reviews (protocol ID: CRD42021214339) and complies with Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) guidelines (Page et al. 2021). The review question and inclusion/exclusion criteria and search terms are presented in Table 1.

2.2.2 Identification of evidence

An electronic search was conducted on 01 July 2020. The following electronic databases were queried: PsychInfo (OVID), PubMed, Science Direct, SPORTDiscus (EBSCOhost), Web of Science, and the Cumulative Index to Nursing and Allied Health Literature (CINAHL) (EBSCOhost). The search terms included: (sport-related concussion OR SRC OR mTBI OR mild traumatic brain injury) AND (diagnosis OR treatment) AND (sport). Articles met inclusion (eligibility criteria) based on the following priori inclusion criteria: (i) participants were involved in professional/elite, semi-professional/sub-elite or amateur (club) sport at the time of injury; (ii) individuals aged 18 years or greater; (iii) concussion diagnosis assessment was administered acutely (here, we define acute as ≤ 7 days of injury); (iv) peer-reviewed journal articles published since 2015. Articles before 2015 would not be reflective of concussion recognition strategies as outlined in the most recent Concussion Consensus Statement (2016). However, part of our a-priori inclusion criteria was modified. For this review, we allowed for the inclusion of athletes younger than age 18 years (e.g., studies with an age range of 5 – 23 years). These studies were considered important as a majority of athletes in these included studies were 18 years or older. Studies in which all participants were under 18 years of age were not included. Full detail on the search strategy and inclusion and exclusion criteria are reported in Table 2.1.

2.2.3 Selection of evidence and data extraction

Following the compilation of online search results, record titles and abstracts were screened by four authors (CC, ED, MMD, AJP), full-text articles were reviewed by five authors (CC, ED, MMD, AJP, LR). The reference lists from review articles were assessed for pertinent studies that may have been overlooked. Data extraction was performed independently by two authors (GS and ED) and data was reviewed by a third author (CC) for consistency and accuracy. In cases of disagreement at any stage, consultations with other authors (CC, ED, MMD, AJP, LR) were planned and disagreement was resolved by joint discussion and consensus. Figure 1 illustrates the literature review process using PRISMA flow chart (Page et al. 2021).

2.2.4 Data synthesis, statistical analyses, and assessment of the overall quality of evidence

References were managed in EndNote (Clarivate Analytics, Berkeley California, USA), and extracted data were collated in Excel 2013. The overall quality of evidence for each outcome was assessed by using a modified Downs and Black (Downs and Black 1998) checklist for measuring study quality by three authors (AP, ED, LR). Higher total scores for this checklist reflect increased study quality and confidence in conclusions, but we used the stratification of poor (< 7), moderate (8 – 15), good (> 16). However, as some questions were not pertinent to this review, a modified form of the checklist was used for a maximum score of 22. Due to the heterogeneity of the studies, a meta-analysis could not be performed, and a qualitative analysis of the studies was instead conducted.

Table 2.1. PICO-model and Medline search strategy in accordance with PRISMA statement

Primary review question/aim	
What are the current *sideline screening methods used to establish the diagnosis of acute concussion or suspected concussion across sports in an adult population?	
Inclusion criteria	
Population	Athletes aged 18 years or greater, involved in amateur, semi-professional or professional sport and sustaining a suspected concussive injury
Intervention	Any sideline* screening assessment used to detect suspected concussion following sports-related head impact event in the acute phase of injury. For the purpose of this review the acute phase of injury will be defined as minutes after the event up to and including 7 days post event. These will include (but may not be limited to) reported (i). Concussion 2, (ii) mTBI, (iii) Cervical neck injury.
Outcomes	Acute concussion diagnosis methods
Study design	Published research, retrospective data analysis, cross sectional study design, parallel studies, prospective, observational, systematic reviews where data meeting the PICO can be extracted. Abstracts (with data) will be included initially. Research published from 2015 onwards.
Exclusion criteria	
Population	Not related to sport, animal studies, <18 years only
Intervention	Non-sideline testing, testing conducted >7 days post event
Outcomes	Concussion/suspected concussion not examined sideline or diagnosis assessment requiring advanced medical training/technology or referral to secondary care in order for diagnosis to be made.
Study design	Case reports, editorials, commentary's, review articles (in the case of systematic reviews if relevant data cannot be extracted or does not meet PICO), consensus statements, position stands and non-English publications. Research published in 2014 and prior.
Search strategy	
†((sport related concussion OR SRC OR mTBI OR mild traumatic brain injury) AND (diagnosis OR treatment)) AND (sport)	

*'Sideline' is used generally to denote testing away from the immediate sporting environment, for example rink side, track side, locker room, medical room, touch line and so on. †MeSH terms were exploded to include more specific terms; MeSH terms were translated into the appropriate subject headings for other databases. Keywords were the same for each database searched.

2.3 Results

2.3.1 Study selection

A total of 7679 citations were screened for eligibility, with the full text of 258 articles retrieved for detailed evaluation. Twenty-six studies met the inclusion criteria following full text review. Figure 2.1 (page 30) presents the PRISMA flow diagram of identification, screening, eligibility, and inclusion criteria for the literature review of side-line diagnosis of concussion. Table 2.1 (page 28) presents the studies meeting the inclusion criteria.

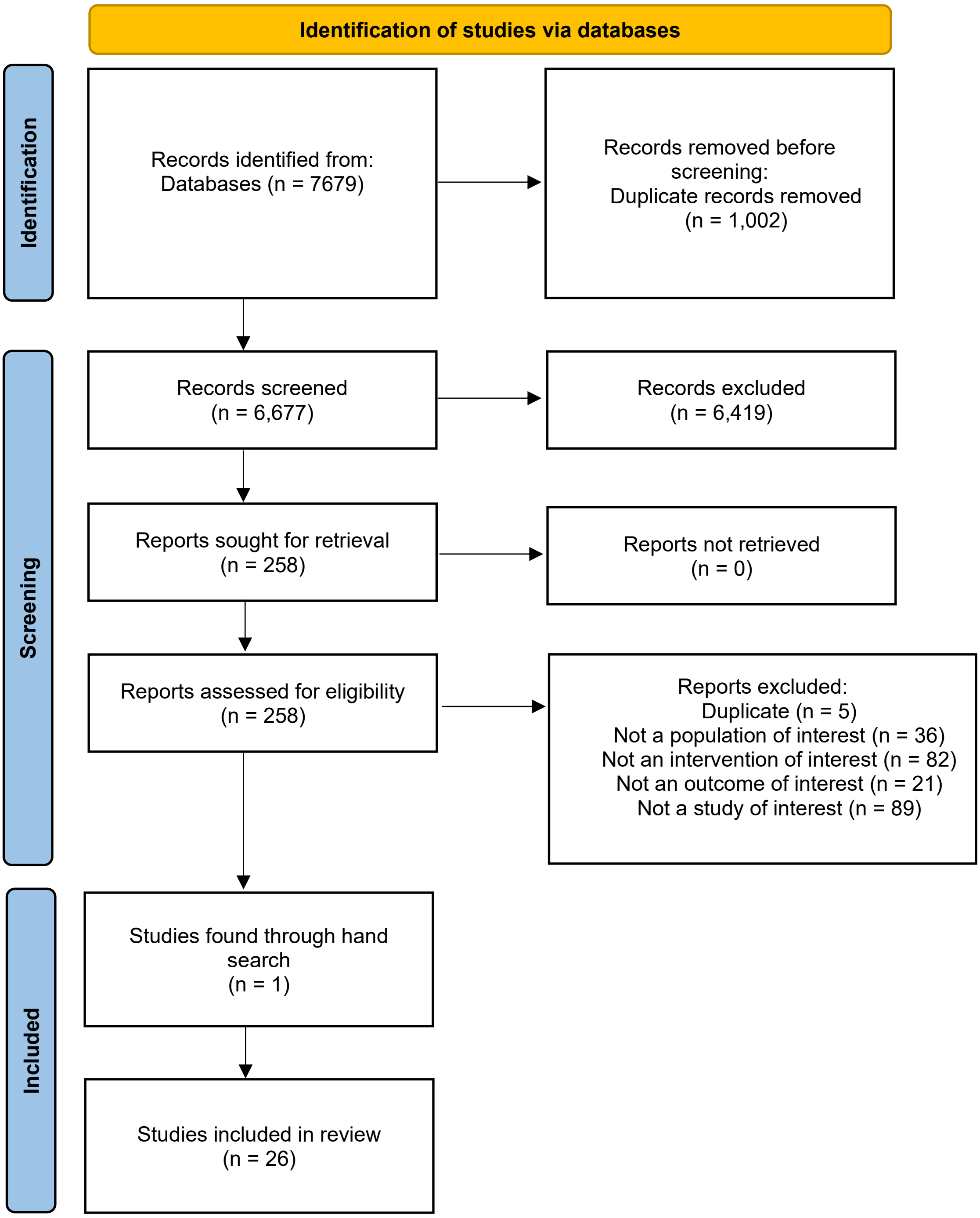


Figure 2.1. Preferred Reporting Items for Systematic Reviews and Meta-analysis flow chart of the studies included in the review.

2.3.2 Characteristics of included studies.

Twenty-six studies (Table 2.2, page 34) met the review inclusion criteria and reported interpretable data on side-line assessments for the diagnosis of concussion. Characteristics of the included studies are summarised in Table 2.2 (page 34). Studies consisted of prospective (n = 12), pilot (n = 2), cross-sectional (n = 2), prospective observational (n = 1), prospective longitudinal (n = 1), cohort (n = 1), observational (n = 1), descriptive (n = 1), prospective cross-sectional (n = 1), pilot case study (n = 1), case-control (n = 1) study and retrospective (n=2). Gender was reported in 24 of the 26 studies with a total population of 7127 participants (5449 males and 1678 females). Twenty studies examined baseline to post-concussion testing. The remaining six studies examined post-concussion exclusively. All studies assessed concussion within the acute diagnosis phase (≤ 7 days). A definition of acute concussion diagnosis was defined in the included studies within the first 3 to 5 days post-concussion (Downey et al 2018), ≤48 h after concussion for SCAT3 (Oldham et al 2018), 24–48 hours for BESS, SAC testing, subacute measures of neurocognitive impairment (i.e., ImPACT at 5–7 days and 10–14 days postinjury) (Sufrinko et al. 2017), 24 h (Vartininen et al. 2016) and 72 h post-injury (Broglio et al. 2019) . Included studies were conducted between 2015 to 2020 in a range of countries, including the USA, United Kingdom, Finland, Australia, Canada, South Africa, and New Zealand.

2.3.3 Test Categories

Included studies (Table 2.2, page 34) used a battery of tests in the diagnosis of side-line concussion (i.e., 'side-line' refers to pitch-side, rink side, changing rooms, or an assessment area immediately available that is not a clinical or hospital setting), that fell into three main testing categories (i) cognitive, (ii) observational and (iii) visual. Fifty-six percent of studies employed cognitive tests, 8% observational, a further 8% visual and 28% used a combination of the three test categories. Nineteen studies used one test category, six studies used two test categories and one study reported the use of tests within all three categories.

Cognitive tests were most commonly employed (n=16) with a combination of cognitive and observational tests used in a further four studies (Sufrinko et al. 2017, Galetta et al 2015, Marinides et al. 2015, Graves et al. 2016). Two studies used a combination of cognitive and visual Russell-Giller et al. 2018. Fallon et al. 2019). Of the 16 studies that recorded the use of cognitive tests, seven studies used one cognitive test, six studies used two cognitive tests and one study used three cognitive tests. Of the studies that recorded the use of observational testing only, one study used one test while the second study used three testing methods. In the two studies that used visual tests exclusively, one test method per study was recorded. The remaining seven studies (Oldham et al. 2018, Galetta et al. 2015, Marinides et al. 2015, Graves et al. 2016) used a combination of cognitive and observational test methods, cognitive and visual test methods (Russell-Giller et al. 2018, Fallon et al. 2019) or all three test categories (Broglio et al. 2019).

2.3.4 Tests and screening methods used.

A total of 20 different concussion diagnosis tests were employed across all studies, differing in frequency. Tests included King-Devick (KD; 10 studies), Sports Concussion Assessment Tool (SCAT) version 3 (SCAT3; 10 studies), Balance Error Scoring System (BESS; 5 studies), Standardised Assessment of Concussion (SAC; 5 studies), tandem gait (TG; 3 studies), immediate post-concussion assessment and cognitive testing (ImPACT; 4 studies), video assessment (VA; 1 study), SCAT version 2 (SCAT2; 2 studies) and vestibular and oculomotor screening (VOMS; 2 studies). The following 11 tests were used once within the range of 16 studies (Brief Symptom Inventory-18, Gait Initiation, Mobile Universal Lexicon Evaluation System, Pitch Side Concussion Assessment, BTrackS Balance Test, Post-Concussion Symptom Scale, Pitch Side Concussion Assessment (version 2), CogSport, modified Balance Error Scoring System, Motor Cognitive Test battery, SCAT5). SCAT3 was used on its own in three studies(Downey et al. 2018, Fuller at al. 2015, Hänninen et al. 2018). Three studies used SCAT3 and KD testing in combination with each other (Harrold et al. 2017, King at al. 2015, Seidman et al. 2015). Three studies used KD, individually (Russell-Giller et al. 2018, Hecimovich et al. 2018, Fuller et al. 2020). One study used TG testing along with a combination of cognitive tests (Galetta et al. 2015) . VOMS was used along with a set of cognitive/cognitive and observational tests (Broglio et al. 2018, Russell-Giller et al. 2018). One study assessed the diagnostic accuracy of their own developed HIA test which incorporated elements of the SCAT3 (Fuller et al. 2020).

2.3.5 Administration of tests

Tests were administered by medical and non-medical personnel. Eighty-eight percent of participants were tested for concussion by doctors, clinicians, orthopaedic support, neurologists, or the assistance of certified athletic trainers or physiotherapists. Twelve percent of studies used team members, trained volunteers, or the study research coordinator to conduct side-line concussion testing for scientific purposes only.

2.3.6 Level of sport

A range of different sports and levels of participation were reported in the included studies. For example, sports included rugby (union and league), American Football, ice hockey, baseball, soccer, Australian rules football, basketball, volleyball, and wrestling. The sport activities can be divided into two different levels of participation;(1) professional/elite, semi-professional and (2) amateur/club, community level sports, 56% of participants fell into the professional/elite or semi-professional levels of sport, 36% were categorised as amateur/club or community sports. Another 4% were classified as a mixed-level cohort of participations who were professional/elite, semi-professional, and amateur level athletes within a study. The remaining 4% did not state the level of sports played by those participants, however, it is important to note the study did not report the level of sports played and testing was carried out within a multidisciplinary concussion centre.

2.3.7 Most significant symptoms

Two studies employing the SCAT3 reported symptom frequency. Fatigue or low energy, along with neck pain (Fuller et al. 2015) and pressure in head, headache and "don't feel right" (Hänninen et al. 2018) were reported as the most common post-injury symptoms. One study (Gardner et al. 2017) observed "slow to get up" a total of 2240 times on 223 different occasions. Signs of "clutching" were reported 212 times during concussion assessment (58.7%). Other concussion diagnosis signs reported within this study included unresponsiveness (n = 52), gait ataxia (n = 102), vacant stare (n = 98), and a post-impact seizure (n = 4). The study by Fuller et al. (2020) asserted that self-reported symptoms and observed clinical signs were the strongest predictors of diagnosed concussion, while conversely immediate memory, tandem gait and Maddock's questions were weak and not significant predictors of concussion.

2.3.8 Test scores and gender

Two of the 26 studies examined the comparison of test scores between females and males. Results were significantly different when compared to each other. Both studies used SCAT3 as part (Harrold et al. 2017) or all (Downey et al. 2018) of the testing protocols. It was clear the results were not similar when compared to each other and further investigation is warranted. For example, Downey et al. (2018) reported that while using SCAT3, male participants reported significantly more symptoms ($p = 0.012$), of greater severity ($p = 0.025$); and performed significantly worse on the SAC compared to females ($p = 0.012$). While the study by Harrold et al. (2017) reported that using SCAT3, women reported more total symptoms ($p = 0.001$, linear regression, accounting for age) and had higher symptom severity scores ($p = 0.006$).

Table 2.2 Overall study characteristics, level of evidence, and modified Downs and Black checklist (maximum score 22).

Author (Year)	Study Type	Level of Evidence	Assessment	Sample size (Concussed/Control)	Sex M/F	Mean Age (Range) Years	Sport	Test Post-Concussion	Score (max 22)
Broglio et al.	PCS	III-2	BESS, SAC, SCAT5, ImPACT, VOMS, BSI-18	N = 1458	919/539	19.0 (N/A)	NCAA (sport unspecified)	3 times in 72hours (h): 0–1.25 h (side-line),1.25–24 h (post-event), 24–72 h (clinic)	17
Buckley et al.	Cohort	III-2	GI	N = 84 (42/42)	40/44	19.2 (N/A)	NCAA (sport unspecified)	24 hours	16
Downey et al.	PCS	III-2	SCAT3	N = 45 (23/22)	19/26	20.0 (N/A)	Football, rugby, ice hockey, soccer, lacrosse, basketball, volleyball, field hockey, baseball, wrestling	3 to 5 days (acute), 3 weeks (post-acute)	14
Fallon et al.	PCS	III-2	MULES, SCAT3	N = 681 (17)	422/259	17 (6-37)	Ice hockey, soccer, football	Side-line	13
Fuller et al.	Cross Sectional	III-2	SCAT3	N = 639 (24)	All male	27.4 (N/A)	Rugby	After game of injury	14
Fuller et al.	Pilot	III-3	PSCA1	N = 165	All male	N/A	Rugby	Side-line (Time frame not stated)	17
Fuller et al.	PCS	III-3	KD	N = 261	All male	27.6 (N/A)	Rugby	48 hours	18
Fuller et al.	RCS	III-2	HIA01/ SCAT3	N = 1265	N/A	N/A	Rugby	Side-line	16
Galetta et al.	PCS	III-2	KD, SAC, TG	N = 332	192/140	11.0 (5-23)	Ice hockey, lacrosse	Side-line /rink-side. (Time frame not stated)	15
Gardner et al.	Observational	IV	VA	N = 400	All male	N/A	Rugby league	N/A	
Goble et al.	Cross-Sectional	III-2	BBT	N = 25	11/14	20.7 (N/A)	College athletes- (unspecified)	48 hours	9
Graves	PCS	III-2	SOT, BESS	N = 15 (15)	All male	18.9 (N/A)	Football	1-14 days	15

Hänninen et al.	PCS	III-3	SCAT3	N = 283 (27)	All male	27.0 (N/A)	Ice hockey	24 hours	15
Harrold et al.	PCS	III-3	KD, SCAT3	N = 426	177/249	35.0 (N/A)	Sport, other	N/A	16
Hecimovich et al.	PCS	III-2	KD	N = 22 (7/15)	All male	19.6 (N/A)	Australian football	10-20 min post-game	14
King et al.	PCS Observational	III-2	KD, SCAT3	N = 104 (52/52)	All male	23.7 (N/A)	Rugby	Days 3, 7, 14, and 21	15
Leong et al.	PCS	III-3	KD, SCAT2	N = 127 (11)	119/8	19.5 (N/A)	Football, basketball	N/A	17
Marinides et al.	RCS	III-3	KD, PCS, SAC, BESS, ImPACT	N = 221 (30)	150/71	N/A	Football, lacrosse, soccer	87mins	14
Merritt et al.	PCS	III-2	PCSS, ImPACT	N = 846 (86)	637/209	19.9 (N/A)	Football, basketball, ice hockey, soccer, lacrosse, wrestling, other	2, 7, and 14 days post injury.	18
Molloy et al.	Descriptive cohort	III-2	KD, PSCA2, CogSport	N = 176 (19/33)	All male	23.8 (N/A)	Rugby	48 hours	18
Oldham et al.	Prospective, longitudinal	III-1	TG, BESS, mBESS	N = 76 (38/38)	All male	N/A	NCAA student-athletes	<48 hours	16
Putukian et al.	Prospective cross-sectional	III-1	SCAT2	N = 263 (85/178)	184/79	20.3 (N/A)	Football, rugby, volleyball, football, crew	0.52 ± 1.18 days	13
Russell-Giller et al.	Pilot	IV	KD, VOMS	N = 71	N/A	14.0 (N/A)	Sports (unspecified), other	1 - 5 days	17
Seidman et al.	PCS	III-3	KD, SCAT3	N = 337 (9/328)	All male	15.0 (N/A)	American Football	72 hours	12

Sufrinko et al.	Case-control	III-2	ImPACT, SAC, BESS	N = 125 (125)	85/40	16.8 (N/A)	Football, soccer, volleyball, basketball, wrestling, ice hockey, softball,	SAC, BESS: 24 to 48 hours, ImPACT: 5 to 7 and 10 to 14	13
Vartiainen et al.	PCS	III-2	SCAT3, MotCoTe	N= 16 (9/7)	All male	23.4 (N/A)	Ice hockey	36 hours	15

N/A: Not available, KD: King Devick test, GI: Gait Initiation, SOT: Sensory Organization, TG: Tandem Gait, GT: Gait Termination MULES: Mobile Universal Lexicon Evaluation Systems, HIA01: Head Injury Assessment Version 1, PSCA1: Pitch-Side Concussion Assessment Version 1, PSCA2: Pitch-Side Concussion Assessment Version 2, MotCoTe: Motor Cognitive Test Battery, VOMS: Vestibular/Ocular Motor Screening, SCAT2: Sport Concussion Assessment Tool Version 2, SCAT3: Sport Concussion Assessment Tool Version 3, SCAT5: Sport Concussion Assessment Tool Version 5, ImPACT: Immediate Post-Concussion and Cognitive Testing, SAC, standardized assessment of concussion; PCSS: Post-Concussion Symptom Scale, VA: Video Assessment, BESS: Balance Error Scoring System, mBESS: modified Balance Error Scoring System, MotCoTe: Motor Cognitive Test battery, PCS, prospective cohort study; RCS, retrospective cohort study

2.3 Discussion

This systematic literature review is an analysis of current side-line assessments for the diagnosis of concussion in adults participating in professional, semi-professional and amateur sports. A definition of 'pitch side' in this review included side-line, rink side, changing rooms, or an assessment area immediately available that is not a clinical or hospital setting. The focus for this review was from 2015 onwards to align with the most recent consensus statement of concussion in sports (October 2016), as the authors deemed any study carried out prior to that year (2015) would be outdated. The main findings showed studies overall were of moderate to good quality (Jäkel and von Hauenschild 2011)and a variety of cognitive, observational, and visual tests were utilised pitch side by mostly medical and allied health personnel (e.g., physical therapists) to assess acute concussion in adults. However, the review also found that the majority of studies have investigated mostly professional/elite or semi-professional cohorts, aligning with these studies likely having access to medical and allied health staff to undertake these assessments. Conversely, the limitation in non-medically trained researchers operating assessments is likely to be contributing to the paucity of studies being undertaken at non-elite/club levels of participation where research is urgently required.

Key findings from the qualitative review showed a large range of different assessments used to quantify concussion. Interestingly, we found that less than half of the studies employed the SCAT assessment (either SCAT2, 3 or 5 for this systematic review). We found this observation surprising given that it has been suggested that the SCAT is the most widely accepted and deployable sports concussion assessment and screening tool currently available (Echemendia et al. 2017). We appreciate that the use of SCAT in research is not a mandatory requirement, and that the objective of studies would be to test the efficacy of other modalities and cohorts, such as in a laboratory environment. However, in field studies such as those included in this review, to reduce disparity in findings, the SCAT assessment should be used consistently across future studies.

The review also found that ~25% of studies used a multi-modal approach to assess concussion by combining two or more testing batteries. While it may be argued that the SCAT does incorporate a multi-modality approach (Mc Crory et al. 2017), there are elements that the SCAT assessment does not measure, such as the oculo-motor system (Echemendia et al. 2017). Indeed, a previous study where the SCAT and an oculomotor test such as the King-Devick (KD) test have been implemented together, results showed a 100% sensitivity in diagnosing athletes suspected of concussion (Ventura et al. 2015). For clinically focused studies and application to clinical-practice, future work should incorporate two or more rapid and non-invasive pitch-side assessments for the diagnosis of concussion to reduce the risk of false-positives or false-negative diagnoses occurring, which may affect follow up results. This has been recently suggested in a systematic review by Harris et al. (2021).

An ongoing concern, particularly for concussion in non-elite/community club-based sports, is the paucity of suitably qualified people who are allowed to administer the SCAT HIA. This is reflected in the current review where the majority of studies used SCAT at professional/elite levels of sport, where access to a medical practitioner was possible. As the consensus statement strictly asserts that only a medical practitioner can administer the SCAT as part of the clinical diagnosis (Mc Crory et al. 2017), this may limit opportunities for suitably qualified scientists who are technically proficient at the SCAT but cannot provide a result, limiting research. Conversely, other assessments such as the VOMS can be delivered by allied health professionals and the KD can be delivered by anyone, increasing their potential usage in research, but due to the aforementioned limitations, this would be without the use of the SCAT (despite assertions that the SCAT is the most widely agreed upon assessment tool for concussion) (Echemendia et al. 2017). As studies have argued that when used in isolation assessments such as the KD or VOMS may not be sensitive enough alone to detect concussion (Fuller et al. 2019, Yorke et al. 2017), we suggest from this systematic review that the SCAT should be incorporated with other testing modalities for data collection purposes, with any clinical diagnosis made by the associated team doctor outside of the study scope.

Interestingly, despite consensus on the use of video identification of concussion (Davis et al. 2019), only one study in this systematic review utilised video. A reason for this was that the video was used for post-event confirmation rather than used for confirmation of concussion at time of the incident. With network media covering professional/elite events, video is easily accessible at matches. However, although multiple and multi-angled cameras are not available at amateur/community club levels, many sub-elite competitions will now incorporate a fixed camera supplied by the clubs themselves or via the local league for streaming or replay on the league's webpage. While not optimal in terms of clarity, it may assist in the detection of concussion, and we suggest that future studies involve video to confirm concussion events to improve study quality. Similarly, we found no studies employing impact sensors in a surveillance capacity. The use of impact sensors (attachments behind the ear or embedded within a gumshield) will assist video confirmation of suspected concussion events, however with no studies to support this hypothesis, we conclude no studies using impact sensors were eligible for inclusion in this systematic review.

Limitations of this review include research involving lab-based clinical assessments. However, the focus of this review was on published research that could assist at the lower levels of sport in community or amateur settings (i.e., in settings where the presence of medical professionals' pitch side may be limited or indeed non-existent). Another limitation we acknowledge is that the laws of each sporting code may not allow for head injury assessments during the game: this may influence the timing of assessments and the ability to 'Recognise and Remove'. In these instances, the general approach would be to remove the participants from the sports activity where there is any indication that a concussion has occurred. These initial sideline tests may be substantiated at a later time using advanced diagnostic techniques by a medical professional or video analysis. The studies included in this review utilised well established testing methods which offered some form of sideline tests for suspected concussions and have highlighted the necessity for a multimodal concussion assessment tool for the initial identification and assessment of concussion. This review highlighted the need for multi-modality concussion testing and that there is a clear disparity in research focusing on professional/elite levels and the lack of studies at amateur/club levels.

2.4 Conclusions

Recognising suspected concussions in sports participants is most effectively realised by using multimodal test protocols that are guided (via primary or secondary confirmation) by medical experts. Based on this review, the KD and SCAT (versions 2 and 3) appear to be the most commonly used tools for the primary assessment of concussion currently. Using additional tests such as VOMS from an observational perspective and balance testing such as BESS show promise in conjunction with cognitive testing. The addition of concurrent video review could potentially offer a promising approach to improve the identification and evaluation of significant head impact events, and a multi-modality-based concussion evaluation process appears to be important to detect delayed-onset SRC, however, current evidence does not support the use of impact sensor systems for real-time concussion screening. As shown in a recent systematic review (Hariss et al. 2021) there is an urgent need to conduct research, using multi-modality assessment methods, but focusing on non-elite levels where concussion injuries occur regularly but a lack of resources and education preclude effective assessment and management.

Chapter 3 – Strengthening cervical neck muscles as a mitigating factor to reduce head injury.

Preamble

Brain injury risk exposure in sport (i.e., contact sports or collision sports) will continue to exist as participants are willing to be involved in these types of sport whilst being aware of the risks involved. Many strength training coaches have suggested that developing better neck strength may act as a mitigating factor against concussion incidence. The primary aim of this review was to investigate methods of neck strength training as a possible way to mitigate concussion. Neck strength has been recommended as a training method in sports such as boxing for a prolonged period. It has been adopted by strength and conditioning coaches as a possible means to make players' necks stronger to reduce the harmful effects of biomechanical forces. The fundamental premise supporting neck strength as a possible mitigating strategy against concussion is based on adding stability to the neck muscles. By stabilising the musculature of the neck, it may be possible for athletes to activate their neck muscles more rapidly to brace for potential impact. Furthermore, it has been suggested that if neck muscles are strengthened, it may be a modifiable factor that can decrease concussion risk across all categories of athletes. It must be noted that scientific evidence in this area is limited and has generally focused on increasing neck girth. The practice of improving neck strength has been anecdotally used by strength and conditioning practitioners across many sports without any evidence that this practice has longitudinal impacts on concussion incidence reduction.

Publication citation:

Daly E, Pearce AJ, Ryan L. A systematic review of strength and conditioning protocols for improving neck strength and reducing concussion incidence and impact injury risk in collision sports; is there evidence? *Journal of Functional Morphology and Kinesiology.* 2021 Jan 12;6(1):8. https://doi.org/10.3390/jfmk6010008

3.1 Introduction

Injuries to the head and cervical spine region are common in collision sports and may result in concussion or mild traumatic brain injury (mTBI). The most recent Consensus Statement on Concussion in Sport (Mc Crory et al. 2017) defined concussion as "a traumatic brain injury induced by biomechanical forces". Included in these biomechanical forces are incidents such as a direct impact to the head, or an impact to another part of the body with a mechanical force transmitted to the head (Collins et al. 2014). The Consensus Statement on Concussion in Sport (Mc Crory et al.2017) also states that there is an absence of clarity around whether concussion can be classified as an mTBI in a clearly defined clinical sense. While concussion may represent a subset of mTBI, it should be noted that mTBI is not a concussion and, as such, the terms should not be used interchangeably (Dimou, 2014)

Moreover, it has been noted that, even though functional brain activation differences can persist up to two months after a concussion has been experienced, performances on standard working memory tasks are comparable to normal controls after the same length of time (Dettwiler et al. 2013). Adding to the complex nature of concussions, research provides support for ongoing physiological differences up to 12 months post-concussion (Pearce et al. 2020). This can manifest as ongoing fatigue that is associated with concussion symptoms as demonstrated by corticomotor and somatosensory measures using transcranial magnetic stimulation (Pearce et al. 2019).

There are documented cases of the connection between collision sports, and long-term concussion injury effects in a variety of professional field sports (e.g., association football (soccer), rugby union, American Football, Australian Football, and rugby league). These associations have found a direct connection between collision impacts, concussion incidence, and long-term neurophysiological or cognitive effects associated with repeated concussion injuries (Pearce et al. 2014). For example, research in American Football has demonstrated that many former players showed high pathological evidence of chronic traumatic encephalopathy (CTE), suggesting that this condition was related to their participation in the game (Mez et al. 2017). In association football (soccer), evidence derived from retrospective cohort studies has shown that mortality rates from neurodegenerative disease were higher compared to other common diseases among former Scottish male professional soccer players (Mackay et al. 2019). In rugby league and recently in Australian football, cases of CTE have been reported from former male professional players who had played more than 150 first-grade National Rugby League and 400 Australian football matches during their careers. This provides persuasive evidence in support of CTE associated with repetitive head injury in professional collision sports (Buckland et al. 2019, Pearce et al. 2019).

The risk of concussion is highest in individuals, whether they are amateur, or elite participating in collision sports (e.g., rugby union, rugby league, soccer, Australian Rules football). The recent data highlight that head and neck injury rates in soccer account for 2.2% of all injuries in the game (Nilsson et al. 2013). The rate of concussion was 0.06 concussions per 1000 h, with a 20-fold higher rate of head and neck injury during matches when compared to training sessions (rate ratio (RR), 20.2; 95% confidence interval (CI), 13.3–30.6) and a 78-fold higher rate of concussion (RR, 78.5; 95% CI, 24.4–252.5). Incidence rates of concussion in other field-based sports such as Australian Football (per 1000 player hours), ranged from 2.24 to 17.63 at elite levels of the game, and 0.35 to 14.77 at the amateur level (McNeel et al. 2019).

The incidence of match concussion in elite rugby union in the UK during the 2017–18 season was 17.9 per 1000 h of match play making it the most common occurring injury in match play (RFU injury surveillance project 2017–18). The most recently available report from community rugby in the UK, reported the incidence rates during the 2017–18 as 3.6 injuries per 1000 match hours, an increase from the previous season (3.0 injuries per 1000 player match hours). The Irish Rugby Football Union (IRFU) injury surveillance report 2018/19 for amateur (non-elite) players reported injury rates for male and female players at 13% (5.7 per 1000 h of play) and 10% (4.9 per 1000 h of play) respectively, which made concussion the highest injury category in males and females during that particular season. For the foreseeable future, it seems difficult to eliminate all incidences of concussion in collision sports, whether they are amateur or elite-level sports (Pearce et al. 2015). This is primarily due to the existing rules, or laws that govern intermittent field sports, and the inherent physicality of collision sports (King et al. 2016). This translates into continuous exposure to serious injury risk and continued concussion risk incidence which can have a long-term impact on cognitive function to the participants involved (Hume et al. 2017) . Therefore, the focus needs to be readjusted to examine what injury mitigation strategies can be implemented to decrease the number of concussions in many collision sports.

In professional sports, neck muscle strength is postulated as a possible method to reduce cervical neck injury and concussion incidence among strength and conditioning coaches. Qualitative research by our group investigating methods to reduce concussions with current professional strength coaches has supported this assertion. Research in youth athletes (<18 years) has suggested that increasing isometric neck strength to stabilise the cervical spine can reduce injury risk when compared to previous seasons' injury data (Hrysomallis et al. 2016). However, the evidence to support that this type of intervention can reduce and/or mitigate concussion in adult (elite or amateur) populations is not evident. This systematic review, therefore, sought to examine the current evidence for developing neck muscle strength to reduce concussion incidence and impact injury risk in adult populations who participate in collision sports at amateur, sub-elite, and elite levels.

3.2 Methods

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were followed when conducting and reporting this review (Moher et al. 2015).

3.2.1 Literature Search

A literature search was carried out in the PubMed, CINAHL, Science Direct, and Web of Science databases. Terms to describe the population (e.g., adult, human) and intervention (e.g., neck muscle strengthening protocols) were included in the search strategy (see Table 3.1, page 45). Criteria for inclusion in this review were: (1) a human adult (≥18 or above) population, (2) involved in amateur, semi-professional and professional sports, (3) involved in collisions with other humans, apparatus or the environment, (4) neck muscle strength intervention (5) outcomes/effects on increasing neck strength in participants and/or injury data, (6) original research, RCTs abstracts (with data/full paper not available) were included initially, and (7) written in English. Papers were excluded if they were theses (PhD, Masters or Honours), not a piece of original research; if the population consisted of animals, a paediatric age group under 18 years of age, a geriatric group who experienced mTBI due to health or illness status, if there were no outcomes of interest; or a study design of interest, or if the study was not an RCT or if it was not an intervention of interest as per the criteria. Papers were excluded where the predominant focus was on kinematics, modelling of impact, or simulated laboratory testing of impact to the head and neck.

Table 3.1. Sample search strategy terminology.

Concept/Term	Synonyms
Neck strength	cervical neck muscle strength OR sternocleidomastoid muscle strength OR musculus sternocleidomastoideus OR cervical range of motion OR isometric neck muscle strength OR neck flexor musculature OR neck muscle strength endurance OR neck muscle strength testing OR active neck muscle training OR neck muscle size OR neck strength measurements OR neck muscle coactivation
Concussion and/or mTBI	concussion OR head injury OR head trauma OR sub-concussive injury OR head impact OR brain injury OR head trauma OR neuroimaging biomarkers OR neuropsychological testing OR eye movement OR cognitive function

3.2.2 Data Extraction

Data extraction was performed by two authors (ED and LR) using a tool adapted from the National Health and Medical Research Council (NHMRC) data extraction tool for RCT and cohort studies. Any disagreements were resolved by a third author (AJP). Information regarding study design, intervention and control conditions, sample size, allocation procedure, population characteristics and relevant outcomes was extracted from each paper. A meta-analysis was not feasible; hence a qualitative analysis of included studies was completed.

3.2.3 Quality Assessment

Quality assessments were performed on all included studies using a Quality Criteria Checklist for RCTs and Cohort Studies (Handu et al. 2016). The tool consists of ten questions for which each paper is given either a 'yes', 'no', 'unclear' or 'NA' response. The research question, study population, intervention and control conditions, outcomes, study design, conclusions drawn, and funding sources were all assessed to determine the methodological quality of each paper. Papers were designated a quality rating of positive, negative, or neutral based on the answers to the 10 questions. The quality rating of each paper was considered when interpreting the results.

3.3 Results

Database searches identified 2462 articles. Following title and abstract screening, 12 full papers were retrieved and assessed for inclusion. Three papers were eligible for inclusion in the review. Figure 3.1 (page 47) illustrates the flow of studies and reasons for the exclusion of full papers. All studies were rated as 'neutral' when assessed for quality.

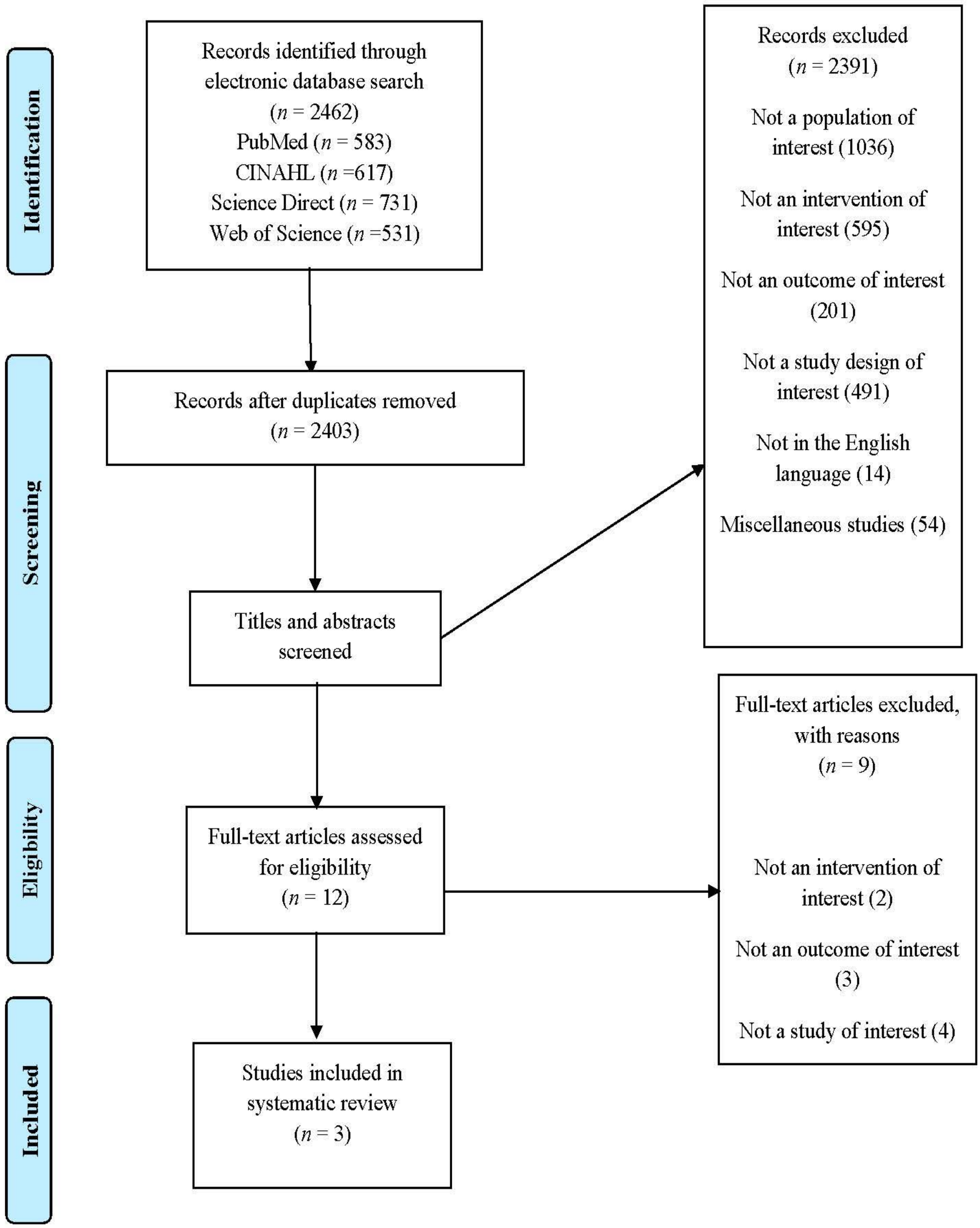


Figure 3.1. PRISMA flow diagram of included studies.

3.3.1 Description of Included Studies

Three studies examined the effects of a neck strengthening intervention on adult athletic populations after gathering baseline measures of isometric neck strength and re-examining neck strength after the predetermined intervention timespan (Table 3.2, page 49). Two of the papers (Geary et al. 2014, Naish et al. 2013) examined standard isometric neck strength as an intervention while one paper (Versteegh et al. 2019) examined a novel neck strengthening device.

Table 3.2. Study design, population, intervention and control conditions, duration and outcomes measures of studies.

Study (Author, Year, Location)	Quality Rating	Intervention Group	Intervention	Control Group	Duration	Outcome	Results
Geary et al., 2014. Ireland []	N	15 male professional rugby union players. (mean ± SD age = 19.33 ± 1.29 years; height 1.85 ± 0.06 m; body mass = 95.15 ± 13.24 kg)	Participants were required to lie supine on a standard gym bench with their feet planted on the floor and their head and neck unsupported. Manual pressure was applied in each direction (flexion, extension, left-side flexion, and right-side flexion) by a professional strength and conditioning coach with the participant being required to maintain their cervical spine in a neutral position for 10 s against the applied manual resistance. In total, three 10-s holds were performed in each direction.	10 semi-professional male rugby union players (mean ± SD age = 20.70 ± 1.25 years; height = 1.85 ± 2.74 m; body mass = 101.30 ± 12.32 kg)	5-week neck strengthening program performed twice per week.	Isometric Neck Strength	No significant between-group differences in isometric neck strength were noted preintervention. A significant main effect for time was observed (*p*, 0.05) -the intervention group increased isometric neck strength in all planes after the 5-week intervention (F preintervention = 334.45639.31 N vs F postintervention396.05675.55 N; E preintervention = 606.19697.34 vs E post-intervention = 733.886127.16 N; LSF preintervention = 555.56688.34 N vs LSF postintervention = 657.146122.99 N; RSF pre-intervention = 570.006106.53 N vs RSF postintervention =668.006142.18 N). No significant improvement in neck strength was observed for control group participants

Naish et al. 2013. Australia [	N	27 male players consisting of 15 forwards and 12 backs (mean ± SD age = 25.2 ± 3.9 years, height 187.1 ± 6.3 cm and mass, 102 ± 11.9 kg).	A progressive and supervised isometric neck strengthening intervention program was added to the overall strength and conditioning program at the beginning of the 2008–2009 pre-season period. Isometric neck strengthening exercises were selected as it was believed that the absence of movement was likely to be of less risk to the cervical disc, facet and neural structures. Exercises that involved producing an isometric contraction directed in axial rotation were not included	No control group was identified	26-week program with two phases; (1) a 13-week strengthening phase followed by (2) a 13-week maintenance phase	Isometric neck strength Reduction in cervical spine injuries	No significant differences were evident between seasons for the number of players with cervical spine injuries (8 players in 2007–2008, 6 players in 2008–2009, p = 0.75) or the total number of cervical spine injuries (12 and 6 for the 2007–2008 and 2008–2009 seasons respectively, p = 0.34). The number of cervical spine injuries experienced in matches decreased (from 11 in 2007–2008 to 2 in 2008–2009). The time loss related to these injuries was not significantly different (p = 0.40) between-season. The initial 5-week neck strengthening program resulted in a non-significant increase in isometric neck strength in all four directions of movement (flexion, p = 0.271; extension, p = 0.481; left lateral flexion, p = 0.687; right lateral flexion, p = 0.711)
Versteegh et al. 2019. Canada []	N	8 male players mean ± SD – neck girth (cm) 43.8 ± 2.3 Age (y) 20.8 ± 1.4 Height (m) 1.88 ± 0.062 Body mass (kg) 112.4 ± 21.5	Quasi-experimental pilot study design with intervention (n = 8) and control (n = 10) groups. The intervention group was trained (twice/week,10 min, for 7 weeks) on a training device that uses self-generated centripetal force to create a dynamic rotational resistance. The protocol was intended to target the ability of the neck muscles to perform coordinated multiplanar plyometric contractions. Both groups also continued with traditional neck strengthening that included training on a straight-plane, isotonic, 4-way neck machine.	10 male players mean ± SD – neck girth (cm) 43.5 ± 3.0 Age (y) 20.8 ± 1.8 Height (m) 1.903 ± 0.056 Body mass (kg) 113.9 ± 20.2	7 weeks	Dynamic and static neck strength	Composite neck strength improvement favoured the intervention group. Mean change in composite strength of the intervention group was 32 N (95% CI, 13–50), whereas in the control group, it was 12 N (95% CI,210 to 34). Performance on the training device showed improvement after routine practice within 1 week, as evidenced by a trend toward increased peak speed in revolutions per minute (RPM). After 7 weeks for the intervention group, peak RPM increased from 122.8 (95% confidence interval [CI], 91.3–154.4) to 252.3 (95% CI, 241.5–263.1).

3.3.2 Interventions

In a study of male professional and semi-professional rugby players, Geary et al. (2014) investigated outcomes after a five-week intervention of specific isometric neck strength training (*n* = 15) using a commercially available digital hand held dynamometer as a measure of overall strength in all planes of motion (i.e., flexion, extension, left side flexion and right side flexion).This study included a control group (*n* = 10) who did not take part in the specific neck strengthening protocol and instead continued their normally prescribed strength program. During the five weeks, the isometric neck strengthening program was undertaken twice per week. The participants in the intervention group were required to wear a custom designed head harness and manual pressure was applied to both the head harness and participants by a professional strength and conditioning coach The participants were requested to lie supine on a standard gym bench with their feet planted on the floor and their head and neck unsupported. They were required to maintain a neutral position in their cervical spine for 10 s against the applied manual resistance of the professional strength coach. Three sets of ten second holds were performed in all planes of motion used for this intervention. The full-time professional rugby players received supervised strength and conditioning training, while the semi-professional rugby players did not receive supervised strength and conditioning support.

The study by Naish et al. (2013) was 26 weeks in duration where the isometric neck strength program was focused on reducing the incidence of cervical spine injuries in the cohort (*n* = 27) selected. No control group was identified for this study, all participants were male professional rugby union players. This study used exercises that focused on isometric strength in neck flexion, neck extension, lateral neck flexion, bent over neck flexion and extension utilising a cable fly machine and a scrum machine. The neck strength intervention was initiated with a familiarisation session and followed by gathering isometric neck strength in four different directions (i.e., flexion, extension, right lateral flexion, and left lateral flexion). Peak isometric neck strength was measured using a head harness made of webbing and Velcro, the harness was attached by a cable to a load cell (HBM 2007 S40 100 kg) which was in turn attached to an immovable metal frame. Before the evaluation of neck strength, each participant was requested to perform three submaximal efforts (75% effort) and asked to hold these contractions for five seconds. Thereafter the participants were asked to complete three, five second contractions, the highest score range of motion (ROM) of these three efforts were recorded. Rest periods (30 s) were integrated to minimise the effect of fatigue between each effort. The testing order was block randomised for this intervention.

Versteegh et al. (2019) evaluated the effects of a neuromuscular neck training device on multiplanar static and dynamic neck strength. Both the intervention group (*n* = 10) and the control group (*n* = 8) were male college American football players (*n* = 10). The intervention group was trained twice per week on a novel device that used self-generated centripetal force to create dynamic rotational resistance over seven weeks. The intervention group of players were fitted with a standard American football helmet with an added attachment on top of the helmet. On the attachment, a 25-cm rod could be extended, and a weight of 125 g was located at the distal end of the rod which was parallel to the floor. The helmet was secured on the head of participants with their back unsupported and feet flat on the ground. Participants created circumduction movements of the head to initiate the weighted rod to spin on its axis while attempting to keep their bodies as still as possible. The increase in spin made the weight (125 g) provide increased resistance using centripetal force. Each participant was asked to complete six sets of fifty revolutions in a clockwise and counterclockwise direction. The weight selection and testing protocol were established by using a sample of the of the target population. Each set was timed with a stopwatch and recorded. A portable computer used on bicycles counted the revolutions and calculated the velocity of each revolution of the set.

3.3.3 Participants

Study populations ranged from 18 to 27 participants (mean = 23). Two studies (Geary et al. 2014; Naish et al. 2013) indicated that participants were male professional or semi-professional rugby players. Geary et al. (2014) included both male professional and semi-professional rugby players, where the professional rugby players (*n* = 15) acted as the intervention group and the semi-professional players (*n* = 10) were the control group for the study. The professional players were a sample of convenience and were 19.3 ± 1.3 years old, had an average height of 1.85 ± 0.06 m and were 95.2 ± 13.2 kg in mass. The control group of semi-professional rugby players were 20.7 ± 1.3 years old, had a mean height of 1.85 ± 0.03 m and an average mass of 101.3 ± 12.3 kg. No exclusion criteria were indicated in this study, all participants were members of the Ulster Rugby Academy or the Ulster Rugby A squad.

The study by Naish et al. (2013) was a retrospective pre-test, post-test cohort study that involved the analysis of two years of retrospective data from a professional rugby union squad who participated in the Super 14 competition. The intervention for the 27 male players involved the integration of the neck strengthening program into an existing 26-week training program, the rationale for selecting isometric exercises was to reduce risk of injury to cervical discs, neural structures and facet joints. The cohort of players had an average age of 25.2 ± 3.9 years, the average height was 187.1 ± 0.06 m and had a mean mass of 102 ± 11.9 kg. The cohort in this study had a split of 15 forwards and 12 backs that were consistent over the two seasons that the data was gathered.

Versteegh et al. (2019) used a cohort of 18 male college students who played American Football, the purpose of the intervention was intended to target the ability of the neck muscles to perform coordinated multiplanar plyometric contractions. The intervention group was selected to reflect the anthropometry of the intervention group where possible. The control group was aged 20.8 ± 1.8 years, compared to the control group whose average age was 20.8 ± 1.4 years. Body mass was similar between both groups where the intervention group had a mean mass of 113.9 ± 20.2 kg, and the control group had an average mass of 112.4 ± 21.2 kg. In terms of height, the intervention group was 1.90 ± 0.056 m, and the control group had an average height of 1.88 ± 0.062 m.

3.3.4 Outcome Variables

The primary aim of the study by Geary et al. (2014) was to investigate how effective a specific neck strengthening intervention would be on the isometric neck strength profile of professional male rugby players. They found that there were no significant between-group differences in isometric neck strength musculature noted preintervention. After the specific neck strengthening intervention, it was noticed that there was a significant main effect for time observed ($p < 0.05$). This was recorded in the intervention group as an increase in isometric neck strength in all planes after the five-week intervention (flexion preintervention = 334.45 ± 39.31 N vs flexion postintervention 396.05 ± 75.55 N; extension preintervention = 606.19 ± 97.34 vs extension postintervention = 733.88 ± 127.16 N; left side flexion preintervention = 555.56 ± 88.34 N vs left side flexion postintervention = 657.14 ± 122.99 N; right side flexion preintervention = 570.00 ± 106.53 N vs right side flexion postintervention = 668.00 6 142.18 N). It was noted that there was no significant improvement in neck strength observed for control group participants. This study stated that it was plausible that a neck strengthening intervention may be effective in reducing neck injuries particularly in physical contact areas during training and game time .

The primary outcome variables in the study by Naish et al. (2013) included the number and type of cervical spine injuries as well as the severity of these types of injuries. The severity was measured by the number of days that the players were considered unavailable for matches and training. Cervical spine injuries that did not result in time loss for matches and training were not examined as part of this study. Characterization of the severity and overall diagnosis of cervical spine injuries were carried out by two senior physiotherapists through a clinical examination. Once a cervical spine injury was recorded, the details were entered into a database using the Orchard Sports Injury Classification System (OSICS), using this system, injuries were recorded using four specific codes; (1) cervical spine facet joint injury (NJXX),(2) cervical disc prolapse (NCLP), (3) cervical facet joint pain / chronic inflammation (NJPX) and (4)cervical disc sprain (NCLX).

Secondary outcome variables for the study (Naish et al. 2013) included the baseline testing of isometric neck strength at the start of the season and week 5 of the intervention. Retesting at week 5 was completed by the professional strength and conditioning staff to observe any acute increases in neck strength during the initial five-week period. The rationale for continuing the neck muscle strength training was based on favourable data from the first 5 weeks which then continued for the remainder of the season of 26 weeks duration.

Following the intervention in this study (Naish et al. 2013), there were no significant differences evident between seasons for the number of players with cervical spine injury (eight players in 2007–2008, 6 players in 2008–2009, p = 0.75) or the total number of cervical spine injuries (12 and 6 for the 2007–2008 and 2008–2009 seasons respectively, p = 0.34). Two players had one or more recurrent disc injuries. While there was no significant difference (p = 0.18) evident between-years for the number of training injuries (one in 2007–2008 and four in 2008–2009) there was a significant reduction (p = 0.03) in the number of cervical spine injuries experienced in matches (from 11 in 2007–2008 to two in 2008–2009). The time loss related to these injuries was not significantly different (p = 0.40) between-season. Specifically, there was no significant difference (p = 0.20) in the days lost from training in 2007–2008 (21 days) and 2008–2009 (17 days) and there was no significant difference (p = 0.14) for the number of days lost from matches in 2007–2008 (79 days) and 2008–2009 (23 days). This study recorded non-significant increases in isometric neck strength in all ranges of motion tested, with no significant increases in isometric neck strength recorded.

Versteegh et al. (2019) examined the primary outcome of the training effect of a novel neuromuscular strengthening protocol on dynamic and static neck strength in a group of male college American football players. From this study , it was concluded that there was a composite neck strength improvement in the intervention group when compared to the control group. The mean change in composite strength of the intervention group was 32 N (95% CI, 13–50), whereas in the control group, it was 12 N (95% CI, 210 to 34). Change in axial rotation strength the direction of most interest, demonstrated the largest mean difference between the control and intervention cohorts of 46 N (95% CI, 9–83) and the largest effect size with 95% CI. There was retention inconsistency between groups, when a sensitivity analysis was applied, in which only eight control subjects were selected as matched to the intervention group, it revealed nearly identical findings to the full sample. All performance parameters showed a qualitative improvement after the seven-week training period.

It is interesting to note that both the intervention group, and the control group continued with a traditional neck strengthening on a straight-plane, isotonic, four-way neck machine in conjunction with the novel multiplanar device for the intervention group. After seven weeks intervention period, the researchers recorded a large positive effect size (Hedge’s g, 0.68) in isometric composite neck strength relating to the intervention cohort when compared to the control group (difference, 20 N:

95% CI, 28 to 48). This study (Versteegh et al 2019) concluded that dynamic training for neck strength may reduce injury risk in concussion or other injury to the head–neck segment.

3.4 Discussion

This systematic review of the literature attempted to evaluate evidence regarding neck strengthening protocols as a modifiable factor in reducing cervical neck injuries and concussion in adult sports populations. This review has highlighted the dearth of evidence in adult populations for prospective interventions designed to reduce concussion incidence and cervical spine injuries. In recent years, it has been proposed that an increase in cervical neck strength may act as a mitigating factor in reducing concussion incidence(Toninato et al. 2018). It has further been postulated that impact location and magnitude could have a greater influence on rotational movement of the head than cervical muscle state (Eckersley et al. 2019) . Other evidence has found that the connection between stabilising the cervical spine area of players and reducing injury risk remains unsubstantiated and requires further research (Hrysomallis et al. 2016). Because of an inconclusive position in adult populations (i.e., whether neck strength does mitigate against cervical spine injury or concussion), it remains important to evaluate novel methods for injury reduction.

Physical impact with opposing players or with the surrounding playing environment plays a part in head acceleration. Therefore, any novel method that influences head acceleration could conceivably mitigate against the physical mechanisms of concussion and cervical spine injury. Recently, it has been discussed that developing neck muscle strength could influence the multi directional movement of the head in contact sports by increasing neck muscle stiffness to 'brace for impact' (Le Flao et al. 2018).

A considerable body of research is required to offer a comprehensive answer to this multifactorial issue. Improving the levels of neck strength as a method to reduce injury risk in adult populations as discussed in the three papers included in this review must be viewed with caution. There is a lack of power in the sample sizes as suitably powered sample sizes are difficult to attain for elite athlete populations.

3.4.1 Interventions to Improve Neck Strength

From the results of the research by Geary et al. (2014), it is not possible to interpret whether the intervention brought about a reduction in the numbers of cervical spine injuries in the participants. This study did not address the positional or unit specific requirements for players of rugby union. There are significant differences from a physiological point of view between rugby union forwards and rugby union backs (Brazier et al. 2020) . This study examined, sagittal plane and frontal plane isometric neck strength alone, it is acknowledged that these two planes of motion are not the only contributing factors contributing to overall neck stability. In conjunction with this, the study(Geary et al. 2014) did not evaluate how the strength program affects proprioception or motor control in the segmental cervical spine. This study (Geary et al. 2014) did demonstrate that there can be improvements in neck strength over a relatively short period. However, it did not demonstrate that the improvements in neck strength would have an effect on reducing cervical neck injury.

3.4.2 Retrospective Analysis

Naish et al. (2013) demonstrated that after a neck strength intervention, there was no significant difference (p = 0.18) evident between playing seasons for the number of injuries occurring in training, or no significant difference (p = 0.20) in the days lost from training for this cohort of professional players. These findings indicate that the introduction and implementation of neck strength development techniques across adult playing populations warrants further comprehensive investigation. Limitations evident from this study were that it was a retrospective analysis rather than a prospective study design such as a randomised control trial. Further limitations associated with the study (Naish et al. 2013) was the reduced number of common participants across the seasons that were analysed. It must be acknowledged that this study dealt exclusively with elite level athletes and for this reason, the findings may not apply to rugby union at amateur or community level players. Furthermore, this study (Naish et al.2013) focused their protocol solely on isometric contractions using flexion, extension, and lateral flexion to the exclusion of contractions utilising other methods such as dynamic contractions, plyometric contractions, or impact anticipation.

3.4.3 Highly Trained vs. Amateur Athletes

Versteegh at al. (2019) had similar limitations whereby the participants were a group of highly trained male athletes and evidence from this study may not be applicable to the general population or non-elite athletes. From this study, it was reported that measurement bias may have occurred because the participants were not blinded to the neck muscle strengthening training program. This may have led to the intervention group applying increased effort into their post training assessments. This study was also limited by sample size and had a limitation in terms of the manipulation of the duration for the training program for the participants involved. Further limitations were evident in relation to the manipulation of sets and repetitions which may have produced a more noticeable effect on the dose–response relationship in this intervention.

3.4.4 Protocols to Improve Neck Strength

The interventions from the three studies included in this review have shown that strength and conditioning protocols can improve neck muscle strength. However, the findings reported are from a narrow focus of sports activity, namely rugby union and American football. Also, the included studies focused on male populations only. This is a concern as emerging evidence is reporting that female athletes are at greater risk of concussions, reporting greater symptom severity and are reporting longer recovery times (Covassin et al. 2018) . Investigation into the possibility of neck strength interventions as a modifiable factor to mitigate against cervical spine injury or concussion in female sport participants is required.

3.4.5 Follow Up Research

A noticeable limitation of the available evidence is whether neck strength interventions manage to protect the players once they have engaged in these types of interventions. There is an absence of follow up research to demonstrate the conclusive effectiveness of these types of interventions in the reduction of cervical spine injury and concussion. Additional research has attempted to review neck strength from alternative perspectives under controlled conditions. For example, one study (Gilchrist et al. 2015) sought to examine the effect of the kinematic response of the head in controlled laboratory conditions. Kinematic studies are useful to determine responses but cannot provide support for a recommendation that strength training of the neck musculature is an effective strategy to mitigate against injury in contact sports.

3.4.6 Limitation of the Search Strategy

The search strategy for this review was aimed specifically at adult populations (male and female) involved in sports activity and excluded studies associated with paediatric populations (participants <18 years old) and geriatric populations. There is evidence to suggest that neck strength measures can be utilized as a screening tool in adolescent populations based on neck circumference and mean head to neck circumference ratio. Collins, et al. (2014) proposed that an increase in neck strength can be used as a means to reduce the odds of concussion risk in high school populations who are engaged in specific contact sports. Their study employed univariate logistic regression to assess unadjusted odds of concussion for derived anthropometric measurements, age, gender, body mass index (BMI), and sport. Their results found that neck strength ($p < 0.001$), gender ($p < 0.001$), and sport ($p = 0.007$) were significant predictors of concussions in unadjusted models. This study adds weight to the proof of concept that neck strengthening may improve concussion risk but again, similar to the studies in the adult population, has not employed an intervention to test this hypothesis. An alternative study has examined isometric neck strength interventions in youth populations which have focused on isometric neck strength with the exclusion of dynamic neck strength or collision anticipation (Mihalik et al. 2011). It is unclear if studies of this kind in youth populations could translate to adult populations based on age, anthropometric and gender differences. A subsequent limitation of this review was the exclusion of studies where there was a combination of populations (i.e., cohorts that included populations <18 years of age and >18 years of age in the same study).

3.5 Conclusion

The evidence in this systematic literature review supports the most recent Consensus Statement on Concussion in Sport (Mc Crory et al 2017) which states that prevention interventions using modifiable risk factors remain unclear in terms of possible interventions to prevent or reduce the risk of concussion in sport. Whether we examine neck strength interventions using gender, age, or under specific category of sports parameters, there is evidence to suggest that athlete education programs can be utilised as a strategy to reduce concussion risk in sport (Fraas et al. 2016, Register-Mihalik et al. 2017, Sullivan et al. 2018). Reporting rates from playing populations and coaches have been improving due to an increase in knowledge and information about concussion (Kroshus et al. 2014, Kroshus et al. 2015, Lininger et al. 2019, Neidecker et al. 2018). However, many incidences of concussion are subjectively reported, consequently there are still discrepancies in understanding the effects of concussion due to misinterpretation of subjective self-reporting, particularly in amateur sports (Fraas et al. 2014, Leahy et al. 2020). The research in relation to the effects of concussion in female sports is under researched in relation to the epidemiology of female concussion rates, symptoms and cognitive recovery post-injury (Covassin et al. 2012). Gaining a more comprehensive understanding of the aetiology of female concussion must be seen as a priority for female sports participants, in relation to symptoms, and inflammatory biomarkers after experiencing concussion (Di Battista et al. 2020).

Practical Applications

Strength and conditioning coaches often cite neck strengthening exercises as a means to mitigate against concussion risk and injury to the cervical spine. This systematic review has shown that research on neck strengthening exercises in adult populations reducing cervical neck injuries and concussion is currently limited. A substantial body of research focuses on head acceleration, rotational forces of the head, and impact measurement to the head. However, these interventions do not specifically offer adequate evidence towards reducing concussion incidence in adult populations. The evidence suggests the need for more research to be conducted in both males and females, in larger samples sizes, with longer follow up periods to test the efficacy of neck strengthening as a means of mitigating the effects of concussion and cervical spine in-juries in impact or collision sports.

Post Publication Reflection

Following consultation with the research team, RCTs were removed from the inclusion criteria and should have been removed from the final published draft (as it was deemed to be too restrictive due to limited availability of research in the area).

Suggested edit to methods section:

'Papers were excluded if they were theses (PhD, Masters or Honours), not a piece of original research; if the population consisted of animals, a paediatric age group under 18 years of age, a geriatric group who experienced mTBI due to health or illness status, if there were no outcomes of interest; or a study design of interest, or if it was not an intervention of interest as per the criteria. Papers were excluded where the predominant focus was on kinematics, modelling of impact, or simulated laboratory testing of impact to the head and neck.

Revised aim:

The aim of this systematic literature was to examine the current evidence for developing neck muscle strength and/or to assess if increasing neck strength could reduce concussion incidence and/or impact injury risk in adult populations who participate in collision sports at amateur, sub-elite, and elite levels.

Chapter 4 - Perception of concussion and injury risk in retired professional rugby union players

Preamble

Investigating the means of how concussion is objectively identified and managed in sports settings (professional or amateur) is multifaceted. In conjunction with this, the methods utilised by coaches to mitigate against concussion injury risk can vary and, in many instances, these methods may lack comprehensive scientific evidence to support their inclusion in training programs. Frequently, the voice of the sports participants may not be included when it comes to establishing perceptions of injury risk, how concussions are managed or how coaches can influence player behaviour. This study aimed to utilise qualitative research methods to analyse a series of interviews with a group of ex professional male rugby players (n=23). This study was focussed on how the ex-professional players perceived concussion and the overall risk associated with being involved in a contact sport at an elite level. All participants in this cohort had played rugby at an elite level in various clubs and locations across the globe. Many of the players had played representative rugby for their native countries and had retired from the game in the previous ten years. These players had started their careers in amateur clubs at a young age and therefore had witnessed their transition from amateur players to professional rugby players. The purpose of the interviews was to ascertain what types of pressure they experienced at the highest levels. Pressure from themselves, their peers, and coaches to keep playing even though they may have been concussed or physically injured in another capacity. A reflexive thematic analysis was utilised for these semi structured interview formats. As many current practices that occur in professional rugby union filter into the amateur game, these interviews could inform current practice in the non-elite levels of the game. Please note that the data set used in chapters four, five and six of this thesis were generated from the same set of interviews. This interview process enabled the primary author to identify different research themes and publish three separate qualitative chapters.

Publication citation:

Daly E, White A, Blackett AD, Ryan L. Pressure. a qualitative analysis of the perception of concussion and injury risk in retired professional rugby players. *Journal of Functional Morphology and Kinesiology. 2021 Sep 21;6(3):78*. https://doi.org/10.3390/jfmk6030078

4.1 Introduction

Rugby union has been a professional sport (for males) since 1995. It is a collision sport that is highly physical in terms of impact with opposing players, resulting in frequent contact events and collisions throughout a match. The amalgamation of very high physical demands, combined with regular impacts with opposing players, for example, tackling, scrummaging or mauls, means that injury is an inherent risk of the game. In a study examining 12-month match exposure in professional rugby union players, it was proposed that accumulated training workload and recent match exposure influence a player's current injury risk (Williams et al. 2017). This study demonstrated that players who had played a high (≥35) or a low (≤15) number of matches in the previous year were more susceptible to injury.

This results in players potentially enduring numerous injuries throughout a season in professional rugby (81 per 1000 h (95% CI 63–105), and 3 per 1000 h (95% CI 2–4) during training), and a similar level of injury exposure (ice hockey incidence rates of 79 per 1000 h and rugby league injury incidence rates of 68 per 1000 h) when compared to other collision sports (Williams et al. 2013). As such, overall player welfare is the collective responsibility of coaches, team owners and individual players in professional rugby, as it can have a direct impact on players' physical and mental health (Quarrie et al. 2016). At professional levels, compared to rugby at amateur levels, injury risk is significantly higher in terms of physical injury and concussion risk exposure during contact events (Hind et al. 2020). In conjunction with these factors, professional players often downplay or underreport concussion incidence and physical injury during their professional rugby careers (Cunningham et al. 2020). Many ex-professional rugby players tend to normalise pain and accept that injury is an integral part of the sport. These beliefs can be reinforced by the environment and become part of the "habitus" of the players involved (Malcolm and Sheard, 2002). The habitus of rugby players includes a subconscious and conscious level of conformity to highly masculine norms and behaviours. These are the accepted behaviours and norms that they *should* display when they are part of a highly masculine environment (Giazitzoglu, 2020). By choosing to accept pain and injury as part of professional rugby, this can evolve into a "culture of risk" for the players involved. By extension, this culture of risk can develop into an unquestioned acceptance of physical injury and concussion risk as a normal part of the sport (Nixon 1993, Pringle and Markula, 2005)

The latent pressure to accept pain and injury risk in sport can become culturally engrained within an athlete's mindset (Curry, 1993). It has been suggested that many athletes accept pain and consider their ability to tolerate pain a particularly strong personal characteristic (Safai, 2003). In a group culture, this pressure can be pervasive and become intrinsically linked to the character of the individuals involved and can be exacerbated by coaching or support staff. Under these circumstances, many athletes may consciously or subconsciously perceive that showing physical or mental weakness could tarnish the perception or "superhuman" concept of elite athletes (Caddick and Ryall, 2012). In professional athletic environments, such as men's professional rugby, a tolerance to injury can be perceived as a characteristic that substantiates their position within a group of fellow professional players. Once concussion and injury risk are accepted as part of professional rugby, a further extension of the culture of risk is to decide not to disclose concussion to medical or coaching staff within a club setting (Fraas et al. 2014).

How can the culture of wanting to play while injured be explained in sport either at amateur or elite level? Research suggests that acceptance of pain can stem from elite athletes trivialising and/or ignoring pain; in these instances, athletes may prefer to self-medicate and disregard medical advice to compete (Mayer and Thiel, 2018). Alternative research noted that rugby players chose to play while knowingly injured because of the "sport ethic" of rugby, where self-sacrifice was a widely established accepted behaviour in the sport, and part of the culture of risk associated with the sport (Madrigal et al. 2015) . Furthermore, it can be argued that the culture of risk evident in professional sport is not evident in other occupations (Hawkins et al. 1999). In tandem with this, there is an acceptance that injury is routine and normal in sport (Messner, 1990) and is exacerbated within rugby union by a willingness to participate whilst hurt (Liston et al. 2006).

The connection between professional athletes and their peers increases pressure to play while injured. The social relations in playing groups generate internal and external pressure to play while injured regardless of the long-term consequences to players' health (Roderick et al. 2000) . The existence of this culture of risk is reinforced by acceptance that injury is part of the game and an aspect that players need to accept to be an elite athlete (Nixon, 1993). This study sought to investigate retired players' understanding of concussion in conjunction with the explicit and implicit sources of pressure experienced in professional rugby union.

4.2 Methods

4.2.1 Study Design

A reflexive thematic analysis was utilised for this research study (Clarke and Braun 2015). The primary goal was to examine retired professional rugby union players' understanding of concussion and concussion experiences within the professional game of rugby union. A secondary goal was to examine the latent (implicit and explicit) pressures of being a professional rugby player with regard to concussion incidence and injury risk (n = 23). A semi-structured guide for the interviews was developed to offer an exploratory account of the players' playing background and experience with concussion.

4.2.2 Eligibility Criteria and Sampling

Semi-structured interviews and reflexive thematic analysis were used. An exponential non-discriminative snowball sampling method was utilised, as the first participants recruited to the study cohort provided other referrals (Biernacki and Waldorf, 1981). All included participants were retired professional men's rugby union players who had ended their playing careers within the ten years prior to the commencement of the study (retirement span 2011–2019). The players described their experiences of being involved in professional sport (professional rugby clubs and/or international rugby union representative level) from their subjective perspectives.

4.2.3 Participant Characteristics

The participants associated with this study had all participated in professional rugby union (n = 23). The following nations were represented: Ireland (n = 17), England (n = 1), Scotland (n = 3) and Australia (n = 2). Of the full cohort of players (n = 23), 14 had represented their respective countries at full international test level rugby (61%). The average career span (years) for the cohort was 9.3 (SD 2.7) years in duration and the average age at time of retirement from professional rugby was 30.8 years (SD 2.9).

4.2.4 Ethics & Procedure

Ethical approval for this study was received via the Research Sub Committee of Galway Mayo Institute of Technology (GMIT; RSC_AC_23062020). Pilot research was gathered from discussions within the research team and exploratory pilot trials of the interview format with potential participants. Data were collected during interviews ranging from twenty-five minutes to seventy minutes in duration with a preliminary conversation with each participant to outline the rationale for the study and how the study would proceed. Each participant was given a participant information sheet with a consent form attached.

4.2.5 Procedure & Data Collection

Before each one-to-one interview (interviewer (ED) & interviewee), verbal consent was attained, and the interview proceeded by using a standardized series of questions across all interviews. Participants were informed that all information gathered would be treated as confidential and anonymised for the purposes of this qualitative study. Post interview, all transcripts were read and verified by an independent reviewer (LR). The data from the interviews were collected sequentially from the participants and the transcripts were analysed once all interviews were completed. The main purpose of the study was to document the pressures of playing professional rugby union as described by a cohort of ex-professional rugby players. In addition, these interviews were used to ascertain their levels of concussion knowledge and the analogies they used to understand concussion.

4.2.6 Data Analysis

After data collection from the interviews, each participant was given an opportunity to comment on the recording and offer clarifying comments on their personal interview. The audio recordings of the interviews were transcribed to Microsoft Word format by the lead researcher (ED). After the transcription process, all transcripts were compared to the audio recordings of the interviews. Using this process for syntax correction, final amendments were made to the transcripts to generate the first draft of interview manuscripts (n = 23). Data were analysed thematically according to the Braun and Clarke reflexive thematic analysis approach, following an update to their original thematic analysis approach (2015). For this study, a critical realist framework was utilised to identify the players' descriptions of concussion and their injury experiences in professional rugby (Clarke and Braun, 2013). From the 23 interview transcripts, the lead researcher identified eight subcategories, which were subsumed into five categories, resulting in four themes. Interview content and themes were independently assessed and reviewed by the third author to assist and finalise the thematic analysis process (Ellingson, 2009).

4.2.7 Researcher Background

The research team nominated ED as the primary interviewer to collect data. This was based on his previous experience as part of a professional rugby organisation and experience in gathering qualitative data. It was determined that the ex-professional players would be more responsive and/or more open in their interview responses with ED as compared to other members of the research team. This could be attributed to the presence of a male interviewer (ED) with prior experience of being part of a professional rugby organisation that would be conducting interviews with male participants (Blackett et al. 2018; Braun and Clarke, 2019). This was viewed as a positive aspect with respect to the recruitment of participants for the study.

4.3 Results

This study examined the pressures associated with being a professional rugby player and the players' understanding of concussion as an injury in professional rugby union. In this study, four major themes were identified by the authorial team. Based on significance, the lead author identified a hierarchical order for these four themes: (1) Medical and theoretical understanding of concussion; (2) Descriptions of symptoms and disassociated language; (3) Concussion experiences, misunderstanding of subconcussive impacts, categories of concussion; and (4) Peer influences on concussion within the sport. Table 4.1 (page 65) illustrates the composition of these themes with regard to the categories and subcategories. Throughout the interviews and the process of theme identification, a connecting theme of language emerged across the four major themes.

Table 4.1 – Retired players' understanding and descriptions of concussion in professional rugby.

Theme	Category	Sub-category	Terminology	Selected illustrative comments from players
Medical and theoretical understanding of concussion	Awareness of the physiology of concussion	Mechanism of concussion	Impact, whiplash injury, shaking the brain, chinned	*"get the impact there going one direction and the impact sends him another direction and it's actually not them hitting the ground. It's the movement of their head at that speed." (**P6)** "it's a blinding concussion……… like a big charge, but it just went through my whole body and then boom, I fell on the ground." **(P3)***
	Non-medical descriptions	Use of analogies to understand and describe symptoms	Déjà vu, brain fog, deep sleep, being drunk, pressure in the head, disorientated, foggy, blacked out	*"It was like being blackout drunk and not remember anything for hours later." **(P5)** "You just feel you know your head full of pressure, I had those mild symptoms, a total pain in the back area or between your eyes and then just tension." **(P21)***
Descriptions of symptoms and disassociated language	Understating the injury and using casual terminology	Dismissive; a non-serious injury	Crack, head knock, bang to the head, run of the mill concussion, spots, stars, blurry vision, bell rung, dizziness, in a haze	*"that spark sort of thing is when you're going to make that tackle and your head in the wrong spot. If someone really winged you in contact, that's what I'm talking about with those one." **(P16)** "To be honest, I'd say, you know, it was one of like it was a kind of what do they call having your bell rung or something like that." **(P18)***
Personal concussion experiences; misunderstanding of sub concussive impacts, categories of concussion	Knock out blows and sub concussive impacts	Knock out blows experience	Numbness, knocked out, panned out, out cold	*"I was knocked out to a point where it's just a real numbness." **(P3)** "I got knocked clean out and I just remember being brought in the car after I've been to the hospital." **(P11)** "I was out cold in the field, tongue going down my throat." **(P15)***
		Understanding concussion and sub concussive impacts	Not fully knocked out, wobbly, gradual onset of symptoms, headaches	*"I know it is a kind of grey area, you know there's a lot of times you know there's a misunderstanding of what I call concussion actually is, I suppose the easiest way, to kind of get this across is that I never I never had a situation where I was not out cold where I was like fully unconscious." **(P17)** "I took a knock to the head and that was another gradual onset like initial thing was quite painful and the session was finished, very hot day as well. It was horrible because they're terrible headache and you know I didn't really want to talk to anyone or anything like that." **(P22)***
		Categories of concussion	Minor concussions, strata of concussions, small episodes	*"It's like a minor concussion and you play on, adrenaline gets through, but the next day your neck and your top your head would be sore to touch." **(P10)** "The minor ones were like suppose any Sunday after a game it will be your sore everywhere. Like my neck and head would have been sore if I got them back.? And for the three or four days and it was like I could feel the side effects. Vision was slightly blurry, I wasn't myself." **(P10)***
		Unacknowledged or hiding concussion symptoms	Shake it off, get on with it, not being right, temporarily not cognitively present	*"You feel like you were there before or yesterday or a week before I've had them for an open side flanker and that would be an as well as a constant thing where you get knocked all different angles." **(P10)***
Peer influences on concussion within the sport	Sporting culture, reinforced social norms	Influences on staying in the game	Loyalty, not admitting being injured, badge of honour, pressure from teammates	*"If you were able to stand up and play on and tackle the fellow in front of you and carried ball and everything, you're not come close enough. You're not concussed enough to go off like it kind of goes back to the point, that unless you're asleep on the field and can't actually stand up, you're staying, and you play on was the prevalent attitude." **(P1)** "Players are pretty sharp these days as well as you know, it's not just a case of 'man up and get on with it'." **(P2)** "The mentality of the whole sport around concussion, there was no talk about them." **(P8)** "I understand guys put pressure on themselves to keep playing and toughen up and you know that is rugby for sure" **(P12)** That's an important thing 'cause obviously there's pressure from your teammates in that sort of natural environment." **(P12)***

4.3.1 Theme 1—Medical & Theoretical Understanding of Concussion

Awareness of the Physiology of Concussion

All players interviewed had a long-term association with the game of rugby. With this association, they had developed a profound connection with the game from an early age, e.g., "I fell in love rugby around 9–10 years of age". This early exposure demonstrated that rugby is a collision sport and has inherent dangers, including concussion risk. Most players recalled being coached from an early age to tackle correctly in an attempt to mitigate concussion risk. These skills, when taught correctly, translated into appropriate tackle technique as a professional rugby player: "I got exposed to good coaching as I was growing up, that's why I love the game and I was lucky enough that I could make a living from it as well". The interviewees expressed opinions that direct blows to the head and neck had the highest probability of resulting in concussion while playing the game: "*When the impacts are coming like you know, the brain shakes in the head*", and *"one of mine was where I got chinned like it wasn't a big collision to the head. It was a hip to the chin, and it was almost like you'd see in a boxing match like a punch to the chin"*, or more clearly expressed as "*I got kicked in the head and then there was a loss of consciousness".*

This anecdotal evidence is supported by injury surveillance evidence, where the highest incidence of concussion occurs in the tackle and/or the contact areas of the game (i.e., tackles, rucks, mauls, etc.). This belief in improving tackle technique in order to reduce concussion risk in players is regarded as valid by many of the players, in terms such as, "*We can coach our young athletes in in their tackle technique as well, I think will be a would be a big defining factor*". There was evidence to imply that incorrect technique leads to concussion and other physical injuries to fellow players: "*so many concussions probably around how you tackle and the breakdown area*", and "*when you look back technically, he wasn't, probably, you know, making tackles the way you should have been*". Other players believed that certain strength and conditioning protocols could be implemented to reduce concussion risk: "*[i.e., increase the] amount of posterior work around the neck within their program as a prevention strategy*" *and* "*I think exercise, probably neck strengthening and I don't know much about it, is possibly going to help (prevent concussion)*".

As the tackle and/or contact areas of the game are unlikely to change, some players were of the opinion that changes to current tackle laws will do little to mitigate against concussion risk.

"Lowering the tackle height further, which has been discussed, would be a mistake. I think that's going to lead to more concussions, because the reality is for someone who is 6'6", if you got to defend two players, all of a sudden, you make a last second decision; my head is the thing that's going to take the bang".

Non-Medical Descriptions & Understanding

While many of the players had a clear knowledge of the mechanism of concussion, the language used was frequently framed in non-medical terms, using analogies to describe the effects "*that kind of Deja vu feeling the kind … where the white stars kind of appear in the corner of your eyes*". It was apparent that the injury was unclear and unnerving for players:

"You got concussed, but it was a massive brain fog. It's almost like when you wake up from a really good sleep and your alarm was going off. But you're not quite sure exactly where you are at that moment".

This sense of disorientation or uncertainty on a temporary basis had led the players to believe that concussion may not have been as serious as other injuries as they could continue to play.

"It's a scary feeling when you're in this situation …… in front of 50,000 people and I've got absolutely no idea where I am or what's going on. You look around like holy fuck what's going on here? I got this concussion".

Assigning non-medical descriptive language, for example, "head knock" or "head bang", to concussion, may have had the effect of reducing the gravity of concussion in a professional environment. The combination of this type of language and a misunderstanding of concussions created an environment where players could continue to play while symptomatic or choosing to ignore that they had a concussion.

"I had a couple of bangs to the head …… at the 2015 World Cup. I did one return to play where I've got head knock, think against South Africa. I managed to play the next week but apart from that I think I had another HIA (Head Injury Assessment) to do…but I've never been knocked unconscious at all in my career".

Many players chose to ignore "minor" concussions and believed that only being knocked unconscious deemed them to be concussed, which was clearly expressed in the descriptive language for concussions in their careers.

4.3.2 Theme 2—Descriptions of Symptoms and Disassociated Language

Understating the Injury and Using Casual Terminology

This disassociation between the injury and the language used to describe it became the normal manner to describe concussion. This type of language seemed to trivialise the injury and cause a disconnection between declarative and procedural knowledge by the players: "*I would have knocks and seen stars … knocked out of whack*". It led to players deeming that they needed to be "knocked out" to be diagnosed with concussion: "*I wasn't knocked out or anything, but just a bit wobbly and had gone through the whole protocol*". It is apparent that players judged their readiness to continue to participate on this metric of being conscious or unconscious and were intentionally dismissive of concussion by using casual language to rationalise the injury. Other descriptions were used where concussions became normalised to the player or were considered an accepted consequence of his occupation. For example, one player described this phenomenon as "*a run of the mill concussion …… one was six weeks long*". This was considered as a standard description which was strongly connected to the previously noted habitus of the environment in which they operated as "tough" professional players.

4.3.3 Theme 3—Concussion Experiences, Misunderstanding of Subconcussive Impacts, Categories of Concussion

Knock Out Blows and Misunderstanding Subconcussive Impacts

The parameters of concussion definitions as described by the ex-players were predominantly related to whether they were knocked unconscious or whether they remained conscious and able to compete.

"I know it is a kind of grey area, you know, there's a lot of times, you know, there's a misunderstanding of what I call concussion actually is, I suppose the easiest way to kind of get this across is that I never had a situation where I was out cold where I was like fully unconscious".

During the interviews, this led to comments about subconcussive hits, and if they had experienced these types of impacts: *"if I got a bang to the head, my memory was wiped for the next 3 or 4 min … I had no idea where you are, then and all of a sudden, the fog starts to lift (and continued to play)"*. It was noticeable that interviewees did not regard these repeated impacts as subconcussive hits; instead, the lack of clarity about what defined a concussion was a dominant collective comment. An example of such a view was seen when one participated stated:

"You (are) like Christ, what day is it? And it's like that instant for a long period of time and it is a hard one to explain the consciousness of a concussion 'cause sometimes you get knocked out cold, sometimes your kind of there with it, and sometimes it's your memories aren't that clearly there, so

it's obviously a difficult one to explain, but it's just sort of a complete reset of your consciousness at the time. "

Categories of Concussion

An extension of using casual terminology was a categorisation of concussion using euphemistic language, such as one participant's explanation: "*A significant difference from that sparkly glitter stars (subconcussive impact) in your eyes to when you get a full-blown concussion. It's important that you know what they feel like*". The connection between a "full blown concussion" with unconsciousness and other concussion experiences where the player could continue was interesting to note. In medical terms, while assessing a concussion, medics can categorise concussion symptom severity using various assessment tools at pitch side or in a clinical setting. The players interviewed had their own stratification:

"I always sort of categorised into maybe 3 different areas; extreme is getting knocked out. Then not getting knocked out cold where you don't know what's happening, you're conscious. Then the kind of where you got a big bang to the head, your vision kind of goes; stays with you for a while, it doesn't go away, can't really function all that well. "

What became explicit from some players was that they were unaware of the cumulative effects of concussion. These cumulative effects may have short- or long-term effects regardless of what category of concussion they had experienced: "*the small episodes are shaking your brain, you know, even some doctors seem to think that they can be as bad as the other ones as well*". As concussion frequency escalated in some players, recovery times from concussion increased concurrently.

"I had five (diagnosed) concussions in my career, but we both know the vast majority of players have a lot more than that, one thing that I always took a long time to recover from a concussion, even very minor ones, like I'm talking three weeks, maybe two months".

Unacknowledged or Hiding Concussion Symptomology

Due to the latent pressure associated with a professional rugby environment, for example, contract and financial issues, it was a common trait for players to feel comfortable being dismissive of concussion. Players expressed this in terms of "*I remember multiple times during my career being very, very dazed on the field*" and in a more subtle sense of when they "*weren't cognitively present during the course of the game*". Many of these occurrences were a clear display of being in an overtly masculine environment and not willing to show any form of weakness as a professional rugby player.

In tandem with these latent pressures, there was evidence to suggest that players are willing to compromise concussion test protocols to remain in the game and hide their concussions,

"I was just talking to this friend of mine who just retired last year. The protocols that were in place, we thought were fairly simple. And we thought that we could kind of trick them …… answer slower and even if you do have to go off and take the test, you're going to pass".

Some players had other methods to strategize around the Sport Concussion Assessment Tool (SCAT) protocols:

"I remember actively practicing those tests, trying to figure out the months of the year backwards, so I could do it or it's 'apple elbow carpet bubble saddle'. So even when I was concussed, I could go into autopilot and beat those tests … you can beat the system".

Even when players felt that they did not play whilst concussed, their comments acknowledged that fellow players continued to play while symptomatic: *"I've without doubt seen people that have been either hit badly or kind of a bit spaced".*

Theme 4—Peer Influences on Concussion within the Sport

Sporting Culture, Reinforced Social Norms

When commenting on the rugby culture that infused their early sporting experiences, it was assumed that playing rugby carried an associated injury risk: "*Even that little bit of stars, that's a concussion, I don't know how many times I got that in my career even all the way up as a kid*". This long-term chronic injury risk was reinforced by culture or familial influences: "*You know what you're signing up for when you're playing*". The inclusive fraternal influence of parents, coaches and peers may not have been openly expressed but it was latently implied:

"Rugby was obviously a massive sport where I was from, my father was big into rugby, the school (I attended) was a big rugby school" and *"I was told afterwards (experiencing a concussion) that I said, 'please don't take me off, my father would kill me' if you take me off'".*

To be perceived as physically weak and conceding to concussive injury was a source of humiliation for players. This was evidenced by comments such as:

"It was pretty similar with the delayed (playing while symptomatic) concussions, just an incident but then afterwards you really didn't feel good at all, I mean, it's not something that you flag on the pitch".

The need to keep concussions hidden was deemed as a necessary action to protect their masculinity: *"at the time and with an ego, I just tried to ignore it (concussion) as much that I could, so maybe I didn't pay attention to it".*

This manifested in a culture where players felt pressure from coaches and peers to be declared fit to play matches because *"you're not going to be the one to report yourself; then you're out for the protocols, which could be up to two, three or four weeks".* Some players voiced opinions where they did not feel secure in declaring their symptoms to coaches and peers: *"like this is the truth, it's very hard to tell because in my early career I didn't even report, I just got back to training and playing".* In other instances, players were unsure whether they were concussed, and chose to say nothing: *"I didn't tell anyone that I was concussed, so I played on, but I didn't know either".* The undercurrent of pressure manifesting from peers and coaches was invariably directed back towards the players:

"It is entirely reliant on the honesty of the players. As I said, the players are fully aware of it (pressure to play), they are competitive animals and they're mad to play, particularly as well when you take in other variables like a guy coming out a contract or fighting for his position".

The risk was inherent during competitive matches and, interestingly, was an accepted part of preparation or training sessions leading up to gameday. From examples of concussion incidence discussed by the players, it was described as an accepted aspect of training.

"I got knocked out by my flatmate at the time in a big contact (training) session, two egos colliding, and I ended up coming out the worst. I got knocked out cold. Sort of one of those ones where it's in the highlights of training and people laughing at it because someone got knocked out cold."

If players received a blow to the head and were possibly symptomatic, it was understood that they would return to play: "*(I) went off to get stitches and didn't feel right …. then the one (concussion) after that which was in training that was just in a maul*", which was the widely accepted practice.

With the benefit of hindsight after retiring from the game, many participants believed that a cultural shift is required in the game. Most participants were aware of concussion being discussed during their professional careers, but a significant emphasis may not have been placed on disclosing concussions or ongoing symptomology: "*In hindsight now, I should have just told the coaches whatever, I was just not right; yeah (taking) a week out, you know that distinction between a concussion and just having a very hard game, maybe talk a little bit more about*". According to one participant, in order to implement meaningful change and avoid the current issues of hiding concussion symptoms or how concussion is discussed within the game, "*there needs to be a change and I think it needs to be cultural change; you stop accepting that this (hiding concussion symptoms or concussions) needs to be part of* *it …… and getting back on a field that is not necessary."* It is evident that cultural shifts to manage pressure within the game cannot occur in isolation and need to be broad and *momentous,* "*whereas in years gone by, it was sort of seen as a badge of a badge of honour, where is now. I think boys are sort of saying 'look, that's not cool'. That's an important thing. 'cause obviously pressure from your teammates and that sort of environment*".

4.4 Discussion

A key finding from this study was the language that male rugby players used when speaking about concussion and their descriptions of pressure in professional sport. The language associated with concussion was influenced by rugby culture and seemed to be quite dismissive of concussions or concussive symptoms. The language used highlighted the various sources of pressure that professional players experience as elite athletes. Many of the obstacles that players faced when attempting to reveal concussions were latent. This unsaid or latent pressure was underpinned by the understanding that saying nothing was a preferable option for their careers. In a historical sense, the emergence of rugby culture is a legacy from the English public schools system that promoted sportsmanship and endurance concerning pain tolerance (Bennett et al. 2018). This historic context partially explains the socialisation of rugby culture, which instilled a tolerance to pain that is generally at odds with what we find in broader society (Pringle and Markula, 2005).

These pressures to accept pain were expressed and understood from an early age, which continued into their professional careers. Professional rugby is a very competitive environment, where the latent understanding is that players need to display durability, strength of character, physical strength, and a willingness to suffer in silence through physical pain and concussion. Many players did not fully understand the ramifications of concussive injury and other injury risk, as it became normalised as part of their sport (Albert, 1999). In parallel, many players did not consider the long-term health implications of experiencing multiple concussions throughout a professional rugby career. This normalisation was supported by trivialising the seriousness of concussions either via dismissive language amongst themselves as players, or from coaching staff. The pervasive culture saw these risks as acceptable and legitimised the value of this ever-present risk for short-term success in the sport (Safai et al. 2003).

It was evident from the interviews that players experienced peer pressure from within the playing group. This pressure was intensified by fellow team members and coaching staff encouraging players to compete while injured. This practice may be understood as a "transfer" of the fear of failure from coaches to players as they (coaches) were under pressure to produce results and win games (Nixon, 1993). The latent pressure expressed by fellow players and coaches either directly or indirectly added to the overall burden that was experienced by the players. This was supported by the notion that being able to endure pain and play injured affirmed rugby players' masculinity and affirmed their commitment to the club (Roderick et al. 2000).

Similar comments were expressed by players who were not first choice or *"fringe"* players. Along with fringe players, some players were either recovering from injury or were injured near contract negotiations. These players were continuously uncertain of their futures as they felt excluded from the core playing group or that their *"credit in the bank"* would be easily forgotten, which led to doubts and issues with self-confidence. It is understandable that the manifestation of these various facets of pressure inevitably led to the players not disclosing concussive symptomology or choosing to continue to play while concussed. The participants in this study opted to dismiss long term physical and mental health primarily for financial gains and to maintain their status as professional rugby players. They managed to rationalise and trivialise the seriousness of concussion, either willingly, or unknowingly by a lack of knowledge about the consequences of multiple concussions and subconcussive impacts during their professional careers. Whether these participants used trivialising language to avoid disclosing concussions or did not understand the gravity of their concussive injuries warrants further investigation. The culture of risk expressed by the ex-professional players in this study accepted that injury risk, including concussion, was an accepted part of the game. In this respect, the players accepted the associated implicit and explicit pressures because they wanted to succeed and be prepared for the stringent demands of elite rugby. It is evident from this study that medics and coaches cannot fully rely on players disclosing concussions or concussive symptoms.

In this regard, players used rationalising language to dismiss concussions or underreport concussion incidence. This was supported by self-imposed implicit pressure and explicit pressure applied by peers and coaches. These verbal pressures were expressed through direct and indirect language from peer groups or by coaches within the organisation. It could be argued that much of the language used was due to a lack of understanding of concussion and the mechanisms of being concussed or external pressures on coaching staff to produce results. In these instances, dismissive language or subtle language cues were used to normalise and rationalise concussion as an injury. This study, therefore, provides valuable detail to inform current professional, amateur, and young players involved in collision sports. This findings from this study may also positively influence older retired players by highlighting areas of awareness and education for their long-term brain health. Due to the lack of research in this area, this study is the first of its kind to examine the pressures on professional rugby players, their understanding of concussion and the language they use to describe concussion.

Many of the participants in this study were dismissive of concussion when they played professionally. Now that many of these ex-professional players are currently coaching rugby at amateur, elite, and professional levels (48%), it is interesting to note their current views on concussion. These interviews highlight the continuing need for education of coaching staff at all levels on the signs, symptoms, and recognition of concussion. These data could assist in eliminating outdated beliefs and the recycling of substandard practice associated with concussion and injury risk. These interviews provide valuable detail on the understanding, thoughts and language used by ex-professional players. This knowledge could assist coaches in understanding the importance of treating concussion as a significant injury and not downplaying the seriousness of concussion in contact sports.

4.4.1 Reflexivity

When examining the research process in this study, it is appropriate to acknowledge that the primary researcher attempted to remain critically aware throughout the process. It was notable that the lead researcher-built rapport with the participants because of prior experience in professional rugby. Many of the participants offered forthright and authentic replies to the interview questions as a consequence.

4.4.2 Study Limitations

At the outset of this study, it was anticipated that interviews would be conducted with elite female rugby players; however, this did not materialise. Research into female elite players and their experiences of concussion is an area that warrants further research. This research paper included players who had retired in the previous ten years and may not be reflective of current practice. It is important to acknowledge that the research team involved in this paper have experience in professional rugby union and therefore the interpretation of the findings is through the lens of this previous experience.

4.5 Conclusions

There exists a disconnect between the language used by players and medical staff when discussing and reporting concussion incidence in the game of rugby. A thorough understanding of how players describe their symptoms is important to enhance recognition of concussion. Future research in this area would require a full discourse analysis of the language that is used by both male and female rugby players at amateur and elite levels of the game. As rugby union is a global sport involving multiple nations where different languages are spoken, discourse analysis can help identify whether these trivialisations of concussion symptoms occur throughout the professional world of rugby. This study also highlighted the fact that many players are dismissive of concussion/subconcussive hits and may not reveal their symptoms to coaches or may downplay their symptoms. Coaches and medical staff should therefore not include players in the decision-making process regarding return to play and should enforce concussion protocols.

Post Publication Reflection

As someone that has worked in collaboration with medical teams in professional rugby for years and as a World Rugby Educator, I am highly familiar with the terminology used by medical staff in rugby settings. I acknowledge that my opinions were reflected in the statement '*there exists a disconnect between the language used by players and medical staff* 'and that the language used by medical staff was not collected as part of this study. This statement should therefore be removed.

Chapter 5 - Injury as an occupational hazard in professional rugby union

Preamble

The aim of this study was to ascertain the rationales of ex-professional players to endure a career in elite rugby union, and how they viewed their 'job'. Being a full-time professional rugby player induces a particular set of circumstances and a mindset that are generally unseen in other professions. These circumstances exist primarily because of the uncertainty of career durations, and the ever-present risk of career-ending injuries. The profession is unique as it is constructed on creating bonds of 'brotherhood' and fostering camaraderie amongst the playing group. These bonds and camaraderie are tested in unique ways as your teammates are also your competition for starting places on the team. Ultimately your teammates are your competition for contracts and your livelihood on a seasonal basis. For players to maintain their contractual status, they invariably needed to hide their concussions or physical injures and, in many cases, accepted injury as part of their contractual obligations. As previously mentioned, many practices that exist in the professional game can be directly or latently evident in amateur rugby. Even though amateur players do not have contracts and have parallel working careers, similar issues exist in the amateur ranks. This study used a reflexive thematic analysis (Braun and Clarke, 2015) as the primary means to analyse the data that was generated by semi structured interviews with the cohort of participants.

Publication citation:

Daly E, Pearce AJ, Blackett, A, Ryan L. Injury as an occupational hazard in professional rugby union: A qualitative analysis of interviews with ex-professional rugby players. *The Journal of Sport and Exercise Science. 2022 Jan 8.* https://doi.org/10.36905/jses.2022.01.04

5.1 Introduction

Rugby union has been a professional sport since 1995 when the International Rugby Football Union Board (now World Rugby) permitted players to be paid to play (Hill et al. 2018). Up to this time, the game was considered an amateur sport, meaning that payments or 'material benefit' to players were not permitted. Professionalism in sport has a notable cost, for example, it has been reported that salaries for marquee professional players in the United Kingdom and Ireland during the 2018-2019 season were more than £600K (Esportif Intelligence, 2018-19). Finance from private sources in addition to lucrative broadcast incentives means that professionalism has changed the game permanently (Nauright and Collins, 2017). With the increase in the monetary value in the game, there are notable financial pressures for players, coaches, and club owners (Nauright and Collins, 2017).

Rugby players are highly trained professional athletes that are required to be in peak physical condition to meet the rigorous demands of the game. Since the introduction of professionalism, players have evolved anthropometrically into larger and more powerful athletes (Quarrie and Hopkins, 2007), inherent in these physical changes are an increased injury risk that is an ever-present threat to the modern player (Williams et al. 2017). Since 1995, rugby players currently see elite rugby as a legitimate career path, and it has been speculated that modern players accept injury risk as being an occupational hazard of participating in collision sports (Malcolm, 2009).

In comparison to amateur players, the injury risk trend is higher in players in the professional game (Yeomans et al. 2018). When looking at physical injury and concussion incidence rates in professional players, the Professional Rugby Injury Surveillance Project report from the UK (2017-18 season) recorded an incidence rate of 17.9 head injuries per 1000 hours of match play (England Professional Rugby Injury Surveillance Project Steering Group, 2018). This equates to 16% of all players experiencing at least one concussion, with 39% of players returning to play within seven days of the injury. Although there is evidence to suggest that there is sufficient knowledge and awareness regarding concussion symptoms and treatment among playing population (Kraak et al. 2019), it has been suggested that there is considerable underreporting of concussion in the game (Clacy et al. 2019).

Many professional rugby players are highly competitive individuals who may choose to disregard their personal health in pursuit of achieving success at the highest levels of the sport (Block et al. 2016). This can manifest in athletes choosing not to disclose their concussion symptoms, as they may experience an internal or external pressure to maintain a silence regarding concussion (Mathema et al. 2016). In this respect, physical injury and concussion can be viewed as an occupational hazard as it almost inevitable that a concussion or repeat concussions will happen to a rugby player during their playing careers (Eagle et al. 2020). The focus of this qualitative research was to explore the undisclosed realities and lived experience of being a rugby player in the professional era. Central to this research was to ascertain how retired rugby players retrospectively viewed injury in their playing careers. With a focus on the effects that professional rugby had on their physical and mental health. Furthermore, these interviews assessed their perception of concussion and what knowledge they had about the potential long-term effects of the physical injury.

5.2 Methods

5.2.1 Study Design

For the purposes of this study, a reflexive thematic analysis was implemented (Braun and Clarke, 2013). A semi-structured individual-interview design was developed to interview retired professional players who had played rugby union to ascertain their physical injury experiences, concussion experiences and concussion knowledge. The interview questions were designed to elicit responses on their playing background that would determine their opinions to physical injury and concussion experience. Participants were sought from various countries and hemispheres to get broad comprehensive perspectives.

5.2.2 Ethics and Procedures

Ethical approval, according to The Declaration of Helsinki, was granted to this study via the Research Sub-Committee of Academic Council of Galway Mayo Institute of Technology (GMIT; RSC_AC_23062020). The initial cohort of participants were identified via the lead researcher by issuing an invitation alongside a participant information sheet, to participate in the study. The preliminary discussions were an opportunity for participants to discuss the aims of the study and how the information would be confidentially managed. Each participant provided informed consent before their interview. Data were collected during interviews ranging from 25 to 70 minutes in duration. It was established that all information would be treated confidentially and anonymised for the purposes of the study.

5.2.3 Participant Characteristics

The participants (n = 23) had retired from professional rugby union within the last 10 years at the time the data were collected. The mean age of the players interviewed was 35.5 ± 4.7 years (range 29 to 43 years old). From the cohort of players (n = 23), 14 had represented their countries at full international test level rugby (61%). The following nations were represented; Ireland (n = 17), England (n = 1), Scotland (n = 3) and Australia (n = 2). The average career span was 9.3 ± 2.7 years and the average age at the time of retirement from professional rugby was 30.8 ± 2.9 years. The playing positions when separated into ‘forwards’ and ‘backs’ were 70% and 30% respectively. Within these two divisions, the following breakdown occurred in the 'forwards' division: front row (n = 6), second row (n = 2) and backrow (n = 8). Within the 'backs' the distribution per population was as follows, winger (n = 2), centers (n = 3) and scrum half (n = 2).

5.2.4 Sampling and Eligibility Criteria

An exponential non-discriminative snowball sampling method was utilised whereby the first participant recruited to the sample group provided multiple referrals (Biernacki and Waldorf, 1981). Participants were informed that they did not have to provide any other potential participants. In many instances, participants provided referrals to other ex-players who were interviewed for this research. The semi-structured interviews allowed a standardised sequence of responses across the participants. This enabled the researchers to identify common themes and/or responses from the participants.

5.2.5 Data Collection and Data Analysis

The responses to the semi-structured interview questions were used to gather evidence regarding their personal awareness of physical injury and concussion whilst they were actively playing professionally. Additional questions were used to establish any perceived impact on their physical and mental health. This study sought to add the 'player's perspective' to the information that national sporting organisations are providing in relation to concussion management and associated symptoms (acute and chronic). These data will provide research aimed at informing current and future players who participate in collision sports about the associated risk of concussion in the short and long term.

Data were analysed thematically according to the reflexive thematic analysis approach developed by Braun and Clarke (2006, 2013) following an update to their original thematic analysis approach. A critical realist framework was utilised to identify and make sense of the players' descriptions of their experiences in professional rugby (Braun and Clarke, 2013).

5.2.6 Transcription

After each interview, every participant was given time to review their interview and offer comments on their personal recording. The audio recordings of the interviews were transcribed verbatim by the lead researcher (ED). These transcripts were cross checked for accuracy against the original audio recordings to edit the transcripts. This involved an initial familiarisation with the content of each transcript by reading and re-reading each transcript to ensure the questions and responses correlated with the audio files of the interviews, this was completed on 4 separate occasions per interviewee. All corrections to transcripts were finally cross checked for trustworthiness by an independent researcher (LR). All efforts were made by the research team to ensure quality in relation to clarity in the transcription, manuscript organisation, with accuracy in the final manuscript drafts.

5.2.7 Coding

Coding, focusing on both semantic and latent meanings was undertaken by the first author (ED) and reviewed with another author (LR). Codes included positive and negative experiences of being a professional rugby player. Theme development was led by the first author in consultation with another author (LR). Initially concussion injury management and safety in the game were scoped as potential themes. The lead researcher identified categories and subcategories for all 23 interview transcripts. During this process, the original list of identified themes were examined, and a quantity were amalgamated as subcategories to reduce the overall number of themes within the study (see Table 5.1, page 88). During the analytic process a flexible and open coding system was utilised to allow for open engagement with the data

5.2.8 Researcher Background

The research team nominated ED as the primary interviewer to collect data. This was based on his previous experience of being part of a professional rugby organisation. It was determined that the ex-professional players would be more responsive and/or more open in their interview responses when compared to other members of the research team. This approach was reinforced as it would be a male interviewer (ED) that would be conducting the interviews with male participants. This was viewed as a positive aspect with respect to the recruitment of participants for the study.

5.3 Results

In this study, two major themes emerged: (1) The realities of being a professional rugby player; and (2) Concussion and injury as an occupational hazard in the professional game. These were further separated into categories and subsequently into subcategories (see Table 5.1, page 88).

5.3.1 Theme 1 - The realities of being a professional rugby player.

Players as commodities & financial incentives

Comments discussing contract negotiations were central to the overall theme of players seeing themselves as commodities while they were playing professional rugby. Many of the remarks related to the fears about being injured or carrying injuries into contract negotiations, for example:

"…It's amazing how much one injury could put you on the back foot in those things (contract negotiations)".

In tandem with physical injury or being perceived as a player who was prone to injury. Other fears were equally prevalent relating to concussion or more accurately, having to disguise concussions to maintain a contract:

"*Because I was out of contract at the end of that season, and I'd had concussions…. I needed to get back and play these games…. It's a horrible predicament to find yourself in"*.

Many players were reliant on their contracts as a source of income, with respect to this, certain physical dangers were expected and accepted:

"I think I'd had like 10 operations in three years; ……then I stopped playing because I wasn't offered another contract".

The physical toll was constant as many contracts were linked to seasonal performance.

"You can get really good money which was hard to get at that stage……but for me it was pretty short, I had four or five good years".

The consequences of continued involvement meant that the dangers were perpetual, for example:

"My career came to an end because of a very bad hip injury which required a hip replacement, it's a difficult way to end your career".

On average most players involved in these interviews were retired before the age of 31 predominantly due to physical injury or concussion frequency.

Being a fringe player (i.e., not a first-choice player) can result in playing contracts that are tenuous and bring their own level of internal or external pressures. The fringe players (n=8) interviewed for this study considered themselves as not being a core player in the team:

"I wasn't fortunate enough to be one of the bigger names. I was not guaranteed to be picked every week…. I could never relax" or *"I always had to be ready…... it was mainly external pressure…...there is pressure put on you (by coaches), 'are you OK, it's a big week for you this week'. Putting all the burden back on you (the player)"*.

It is interesting to note that players felt like commodities to be traded depending on the players ability to remain injury free.

"I mean you're a commodity; that's the way it is going in the modern game. And if you know a player X is earning a couple of hundred grand a year, an' he's missing six months of the season…… because of a concussion, it's difficult for clubs to standby players financially".

This is acerbated when financial pressures impact on the personal lives, when the future for themselves and their families were reliant on remaining free from injury:

"……I didn't have a contract until about three weeks ago and we're moving there now, mentally it can be quite difficult sometimes".

Sacrifice vs. public perception.

Many players expressed opinions that were at odds with what they felt the general public perceived about professional rugby:

"*You're reasonably well paid when you get to a certain level, but what you put your body through (it's) not too much"* or *"I had four or five good years and my head was gone, it became a chore"*.

The ex-players were vocal about how much they had personally 'sacrificed' to become a professional player:

"It's rather time consuming, putting in your effort as a professional athlete, you know there are a lot of choices you need to make about the fallout" and *"this thing (professional rugby) decides everything in your life, especially when family holidays don't coincide with school"* illustrating that it was all-consuming vocation or *a "24/7 kind of job".*

Another aspect that many participants stated was how they continued to play while experiencing concussive symptoms. For example, one participant stated that:

"I saw a noticeable decline in my performance because of them (concussions), a notable decline in my health, my mental health, my physical health I was drinking a lot more, I was taking painkillers".

This manifested as a willingness to compete while being physically injured and declaring themselves fit to play while physically injured:

"But like if a coach asked me could I play the following week (while injured)? I think I did!".

The physical impact of the game was exhibited in a more subtle manner during their careers:

"You see guys who are getting physically sick after games" and when they reflected on their careers post retirement *"not being able to come down the stairs in the morning without using handrails is nice, you're not constantly stiff and sore"*.

Life as a professional rugby player came at a notable personal cost to themselves and those around them:

"…and I just felt you end up giving an awful lot to the sport and my whole life was almost dominated by it" or *"talking to people who have played this sport or are involved in this sport and underestimate what it is, and how aggressive and physical it is"*.

There was an underlying sense that retirement was closure on a meaningful part of their lives. This was reflected in how they spoke about their overall rugby career:

"It is just like an extension to your school days, because it's almost like you go in and get to have a good time with your school mates every day, and even better still, you're getting paid for it".

Nearing the end of their careers provided higher levels of self-awareness for many of the participants:

"You have a certain amount of credit in the bank (as an established professional player) but, as I said, it's amazing how that goes quickly if you get a long-term injury".

Nearing the end of their careers, if they made decisions to seek a contract with different clubs or play in lower leagues, there was a sense of delaying the inevitability of retirement from the game:

"*So, I tore my bicep about two weeks (before a contract renewal); I wouldn't say that was the final nail in the coffin, but it definitely gave me further cause for consideration to hang up the boots or not.*"

The decision to retire and remove themselves from the professional rugby fraternity was also difficult as:

"*Over the space of a few years, where it was, if I'm being honest with myself, it was like delaying the inevitable kind of in a way*".

5.3.2 Theme 2 - Concussion and injury as an occupational hazard

A second theme that emerged during the interviews were that concussion and physical injury were accepted as an occupational hazard. During the interviews, there was a sense of accepted inevitability of physical injury risk and concussion risk from all players interviewed.

Accepted risk of a career in professional rugby

Rugby has inherent risks, and it was clear that many players have been positively conditioned to this cultural aspect of the game; and in many cases this conditioning began at an early age. For example:

"*I fell in love rugby around 9-10 years of age*" or "*you know you play the game because you love it*".

This fraternal culture was reinforced during their careers in terms of viewing professional clubs as an extension of 'school days'. As a consequence, a cultural narrative emerged which acted as enabler to connect successive generations of rugby players:

"*The wealth of experience and knowledge that I come into as a young man, that was unbelievable, and I don't think you realize it when you're doing it at the time*".

This culture pertained to players not wanting to let fellow players down or the club as illustrated by:

"*If you were able to stand up and play on, tackle the fellow in front of you…... you're not concussed enough to go off like. It kind of goes back to the point, that unless you're asleep on the field, and can't actually stand up, you're staying on, and you play on was the attitude*".

An interesting point is how prevalent a self-correcting / self-policing environment was created with the playing groups of which they were members:

"*But that's not just from the coaches, that's just from your peers, your older players, because that's what they used to do. You just suck it up (play injured or concussed) and get on with it*".

Supporting the ethos of playing through injury and being dismissive of concussion; players commented on whether they had 'official' or 'unofficial' diagnosis. In many instances, comments related to this were highly dismissive, either by the language used or the casual manner that concussion was discussed:

"*I may have gotten an undiagnosed one, where I got a bang in the head and then two weeks later, played (another game), that's why I don't have any memory of it*".

Some players comments were illuminating in relation to direct knowledge of how concussions occur:

"*I've no doubt there's been times where I failed under pressure and blacked out…...and within a couple of seconds you're like 'oh geez', it means that's a concussion*".

It's likely that these comments remain the prevalent view towards concussion as rugby is seen as confrontational and demurring from this within a squad context is not acceptable:

"*Guys put pressure on themselves to keep playing and toughen up and you know that is rugby for sure*".

The retired players were vocal about what needs to change in the context of the culture of the game:

"*I think people are going in the right direction, like the whole culture around it (concussion) has changed, I would have remembered years ago, you could have staggered (from concussion), and then it was played in front of the (player)meeting as a bit of a gag like, laughing*".

Players are cognisant that change needs to be implemented beyond a superficial level as:

"*There needs to be a change, and I think it needs to be cultural change; you stop accepting that this (playing while concussed) needs to be part of it……getting back on a field that is not necessary. But yeah, the difference between bravado and being an idiot, really*".

The primary focus of these cultural changes is for the wellbeing of the players. More clearly stated in an alternative manner is how player safety is managed with ongoing revisions to the game and the laws of the game:

"*The kind of culture that we need is to make this game as safe as possible, it's never going to be safe like every time, but you kind of have to have the emphasis that we're doing our best to make it safer*".

Further comments related to these types of changes may be expressed with increased reporting rates and improved concussion recognition protocols:

"*I think why concussion is more prevalent now. It's because, we're actually recognising it with a lower bar than what would have happened 15-20 years ago or more*".

Within these comments, there was a consistent expression of frustration around the injury, namely that it's not a visible injury like a musculoskeletal injury and therefore subject to an undefined recovery time:

"*The frustration with concussion is that it's just unnerving and frustrating, you don't know where the finish line is, so if I ruptured my ACL, I know I'm probably out for about 9 months, give or take a month or two, but with concussion you just don't know, and that's what I find so frustrating about the actual injury*".

Alternatively, some players expressed added frustrations as to how professional players were cleared to return to play much quicker than their equivalent amateur players. This type of 'fast track' recovery for professionals remains an anomaly with the professional game:

"*A guy can get knocked out on a Saturday and if he starts his RTP (return to play) on a Sunday with no symptoms, then he can play again the following Saturday and I don't think that that's right. Like if a guy has visibly lost consciousness or has come close to losing consciousness, I don't see how it's acceptable that he's back on the field seven days later*".

The participants accepted that they had a 'job' where they got compensated for financially. This was expressed as a proud fulfilment of a long-held ambition using terms such as being 'fortunate', 'lucky' or that it was a 'dream' career since boyhood. For example:

"*I've been very lucky with rugby, it's been extremely good to me*" or "*I got exposed to good coaching as I was growing up, that's why I love the game and I was lucky enough that I could make a living from it as well*".

Based on these comments and how ingrained rugby culture is in these players, it is understood that the profession has accepted occupational hazards:

"*I think it (professional rugby) will just continue to be an occupational hazard and people just have to accept that*".

It was repeatedly stated that players accepted these hazards when they signed contracts to play professionally:

"*I think if you sign on the line (contract) to get paid to play rugby. It's your choice and you have to face the consequences*".

As a result, they accepted injury risk and concussion in the short term, along with possible consequences for their long-term health:

"*But like call a spade a spade, if you're messing with someone's brain, you'd stop*" or "*what else can we do to reduce it (concussion)? It's going to happen. It's a contact sport and it's (the game) unpredictable*".

Table 5.1 Results of thematic analysis of retired professional male rugby players' perceptions of physical injury and concussion as an occupational hazard (n = 23)

Themes	Categories	Subcategories	Sample Quote
1. The realities of being a professional rugby player	Players as commodities	Pressure around contract negotiations	"Just every injury came at the wrong time…it's amazing how much one injury could put you on the back foot in those things (contract negotiations)" **(P6)**
		Dangers of professional rugby	"I had neck surgery in 2014. Bilateral stenosis, which is bone growth of both the discs on the C6-C7... I'll get pain in my arms or maybe loss of sensation and it can get quite cramped up a times." **(P9)**
		Being a fringe player	"I was not guaranteed to be picked every week…. dreading the team announcement on Tuesday…I could never relax" **(P25)**
	Financial incentives	Rugby as a business	And it's difficult because it's a business and you know if you're not pulling your weight and your and you're making good money, it's you're going to be on the chopping block." **(P12)**
	Sacrifice vs. public perception	Physical Impact	"You know not being able to down the stairs in the morning without using the handrails is a nice thing, **(P6)**
		Public perception	"I was retired less than a week and I was back working out in an oil refinery." **(P13)**
		Self-awareness	"...that's fine when you're, you know you're a teenager, early 20s and but when you're in your prime and then

			you're in a position again, I wasn't prepared to do it again." **(P22)**
2. Concussion and injury as an occupational hazard	Accepted risk of a career in professional rugby	Culture of the game	"Remember, being in the changing rooms and I'd come after 20 minutes, and I was in my tracksuit after the game and being like what happened, and they were laughing at me." **(P5)**
		Dismissive of concussion	"...on Tuesday or Wednesday before I thought 'I might be concussed here'. It's actually quite subtle... there wasn't a big distinction between maybe being concussed and may just a really rough game." **(P21)**
		Cultural changes in the game	"I think it needs to be cultural change; you stop accepting that this needs to be part of it…getting back on a field that is not necessary. But yeah, the difference between bravado and being an idiot, really." **(P16)**
		Unquantifiable nature of concussion	The frustration with concussion thing that is just unnerving and frustrating about it is, you don't know where the finish line is, so if I ruptured my ACL, I know I'm probably out for about 9 months, give or take a month or two, but with concussion you just don't know and that's what I find so frustrating the actual injury." **(P14)**
		Accepting the consequences of playing pro rugby	So, I think if you sign on the line to get paid to play rugby. It's your choice and you have to face consequences I think." **(P10)**

5.4 Discussion

The primary aim of this study was to clarify the realities and the lived experience of professional rugby from the perspective of ex-professional rugby players. The interviews highlighted that players saw themselves as commodities and were motivated by many factors, including financial reward, adulation of the spectators and latent pressures from coaches or fellow peers. Many players described it as a 'brotherhood' or similarly compared it to 'school days'. In this context, professional rugby provides an unusual dynamic where fellow professionals that are your teammates; can concurrently be direct competition for starting positions or contracts. For example, when teammates got injured, it presented an opportunity to fellow squad members for a starting position.

Intertwined with this dynamic is that the realities of the game are far removed from the public perception. The participants alluded to a misunderstanding of realities associated with professional rugby by the public. The general public didn't see the personal sacrifices, the physical pain or the struggles associated with retaining a contract. These perceptions present a difficult position to rationalise, but it can be partially explained by the veracity that rugby is a highly competitive and lucrative business (Nauright and Collins, 2017).

The Irish Rugby Football Union at the end of the 2018/19 season reported an income surplus of €27.9M in its consolidated financial statement (The Irish Rugby Football Union, 2019). Financial consequences give rise to increased pressures that are transmitted to coaches, directors of rugby, support staff and eventually to the players. Players are valuable assets to the club as they aim to bring success in a sporting sense on the field of play and in a commercial manner off the field of play. The ex-professional players suggested that disclosures of injury or accumulating a series of injuries may be seen in a negative light by the coaching staff or club owners. In this study, many players were fearful of not having contracts renewed because of a current injury (concussion or otherwise) or being perceived as injury prone.

These conditions manifested in players accumulating additional stresses because of fear of being injured around contract negotiations and consequently, at risk of losing their contract. The concept of playing while hurt was supported by important others (i.e., coaches and peers) in many instances. This added additional status for the player when they played while injured, and in effect legitimized any of the short-, or long-term health risks associated with their decisions (Roderick et al. 2000). Other concerns highlighted by the participants were that certain players were treated as 'commodities' due to the highly competitive and pressurised environment. In many instances, players chose not to disclose their concussions to medical staff due to a lack of concussion knowledge and fear of pressures around disclosure that can occur in other sports organisations (Baker et al. 2013). Some participants in this study employed this strategy to retain a contract as their injury status could have directly affected their livelihood, and in these instances, many players opted for silence.

Many of the participants were dismissive about concussion, it was an afterthought and not deemed a severe injury. It was interesting to hear how many participants admitted that they had experienced an ‘official’ or ‘unofficial’ concussion diagnosis. This awareness of ‘official’ or ‘unofficial’ diagnosis was intrinsically linked to disclosure or non-disclosure of a concussion (Ruston et al. 2019). A salient point connected to this categorisation (i.e., official, or unofficial) was how obvious a concussion was to medical teams, or whether the incident was captured on live TV during coverage of matches.

It was evident that most of the participants interviewed did not fully consider the cumulative effects of concussions or sub-concussive impacts (Pearce, 2016). They may not have been aware of the cumulative effect of impacts on their brain health due to a misunderstanding of what is deemed to be a concussion.

This is common in other sports like soccer, where players may have a moderate knowledge about concussion yet continue to demonstrate unsafe behaviour (Williams et al. 2016). Most of the participants were candid about the gaps in their concussion knowledge. Some were unclear about the mechanism of concussion and were equally unclear about recovery times associated with concussion. It appeared that the most inconvenient aspect of being concussed, was the absence of defined timescale for recovery and how intangible the injury remains. They could fully understand and accept a recovery period associated with a musculoskeletal injury. However, concussions were invisible, therefore very difficult to define and quantify, that often led to frustration at not being able to compete (Moreau et al. 2014).

The participants used the word ‘sacrifice’ during the interviews regarding the commitment it took to be an elite athlete (Fletcher et al. 2012). This phenomenon is not unique to elite rugby, as it is common in other sports relating to issues around social expectations and personal identity outside of professional sport (Mc Ewen et al. 2018). The sacrifices required to be a professional rugby player were hidden from the public domain and this duality is conveyed in the language used to describe professional rugby players. In the public consciousness, elite rugby players are described as ‘heroes’ or ‘warriors’ where winning is everything (Douglas and Carless, 2014). The same aspect was evident in this research where it was family members who saw the true constraints of being an elite athlete (Burlot et al. 2018). The realities of professional rugby included concussion risk and being uncertain of employment at the end of any given season. These risks were compounded by the ever-present level of physical danger, as the participants repeatedly stated that there are ongoing exposures to physical risk. These risks are common during the game as it is a collision sport, however, these incidents can occur during training sessions and in competitive fixtures due to the dynamic nature of the game (Fraas et al. 2014).

5.4.1 Limitations

At the outset of this study, it was envisaged that interviews would be conducted with elite female rugby players however this did not occur. Research into female players and their experiences of concussion is an area that warrants further research. This research included players who had retired in the past ten years and may not be reflective of current practice.

It is also worth acknowledging that the team involved in this research are all coming from a background in sport and therefore the interpretation of the findings is through the lens of those with an understanding and previous experience of working in professional rugby.

5.4.2 Implications

Several implications can be drawn from this study. In professional sports terms, rugby remains a relatively young sport, which can be influenced and shaped to create a safer sport. Changing the perception of how concussion is disclosed could have important positive consequences for medical staff and may be a practical means to guide athlete education and the cultural narrative in collision sports. Players must see concussion as an injury and not be dismissive of it. This may require cultural changes in sporting organisations that can be driven by coaches, medical staff, and support staff.

5.4.3 Conclusion

The players interviewed do seem to accept concussion as an occupational hazard of playing rugby. Players viewed themselves as commodities who needed to be 'good value' for the business (of rugby) and were dismissive of the long-term implications of repeat concussions. Given the increasing awareness of the potential impact of concussion on cognitive health it is imperative that rugby is safe at all levels (professional and amateur) and remains a viable option for future players whether this is a full contact sport or non-contact version of the game.

Chapter 6 - Reflections from ex professional rugby union players on law changes, protective equipment, and duty of care in the professional game

Preamble

The primary aim of this study was to assess the experiences of concussion management among ex-professional rugby union players. These experiences elucidated where responsibility rests in relation to objective concussion management, and comprehensive player centred welfare. Intrinsic to this discussion will be the attitudes of the ex-professional players towards coaching staff, medical staff, referees, and owners of professional clubs within rugby union. The participants in this study had extensive experience of sustaining or witnessing rugby-related concussion amongst fellow professionals. In many comments from this cohort, medical staff had the greatest level of concussion knowledge, with coaches having the least amount of concussion knowledge. There exists a distinct disconnection between what players and coaches understood about concussion, using terminology like *"I was knocked-out"* or *"only had a partial concussion".* An overriding aspect of these comments from the ex-professional players seemed to downplay the seriousness of concussion as an injury and many expressed opinions that they did not indicate concussion could impair performance. Some players discussed having a strong medical team with strong opinions as being beneficial to their overall welfare. As many medical staff had felt pressured to clear a concussed player. Many players asserted that protective equipment like gum shields and scrum caps did not prevent or reduce the effects of multiple impacts or reduce concussion injury risk. It was evident that several misconceptions and deficiencies in concussion knowledge were identified amongst this cohort of participants. The data presented in this study could influence amateur rugby union players' attitudes who may accept that protective equipment may reduce concussion injury risk. The opinions of the ex-professional players highlight the need for suitably trained medical staff to be available and remove players who have a suspected concussion from the field of play. This underlines the need for decisions regarding suspected concussion to be as objective as possible whether the players are professional or amateur.

Publication citation:

Daly E, Blackett AD, Pearce AJ, Ryan L. Protect the player, protect the game: reflections from ex-professional rugby union players on law changes, protective equipment, and duty of care in the professional game. *Journal of Functional Morphology and Kinesiology. 2022 Oct 20;7(4):91.* https://doi.org/10.3390/jfmk7040091

6.1 Introduction

Rugby union transitioned to a professional sport in 1995, this evolution meant that professional clubs could be formed from existing amateur clubs, and players could receive a salary (Hill et al. 2018). The change to professionalism was turbulent as many observers considered this a move away from traditional rugby values such as participation being of a higher importance than winning (Collins, 2009). In effect these early days of professionalism led to well publicised disputes between the owners of professional clubs and national governing bodies about access to players (Collins, 2018). The cause of these disputes was primarily financial. For example, during the 2016/17 season, the Rugby Football Union had to pay English Premiership Rugby €244M for using players to represent their countries at international level (Massey, 2019).

Essentially, the level of finance that currently exists in rugby union via private investment and highly lucrative broadcasting deals means that the game has fundamentally changed since the advent of professionalism (Massey, 2019). These pressures to balance financial performance off the field, and sporting performance on the field remains a constant challenge. This is particularly evident for professional rugby union clubs as the potential to generate revenue is not as high when compared to other professional sports such as association football (soccer) (Wilson and Plumley, 2017). This results in a combination of circumstances that creates latent burdens on club owners, coaching staff, medical teams and more importantly the players who undergo the challenge of performing on a field of play every week (Daly et al. 2021).

As rugby players are at the forefront of meeting these challenges, they are now exposed to multiple demands from a wide range of areas. Players are full time professional athletes and are required to be in peak physical condition to meet the rigors of the game (Peek et al. 2021). Since the beginning of professionalism, the anthropometry of players has evolved exponentially over time due to rigorous strength training practices (Bevan et al. 2022, Hamlin et al. 2021). In addition to being physically ready, the stresses of training for competition and competing in matches should focus on individual workload monitoring for player welfare and adequate recovery time (Dubois et al. 2020). These collective requirements exact considerable physical and mental demands from players in terms of the workload volume, on field performance and exposure to injury risk (West et al. 2020).

Research by West et al. (2021) found that injury severity increased in professional rugby union between 2002 – 2019 with tackling accounting for 43% of the overall injury burden (n=10,851 injuries occurred). This research found that the incidence, severity, and burden of concussion increased from 2009-2010 onwards, and from 2011-2019, concussion was the most common injury recorded (West et al. 2021). Athletes have been reported in the literature to not disclose concussions for several reasons. Pressure from fellow players, fear of being omitted from squads, being perceived as weak or the precarious nature of playing contracts have all been reported as reasons for a lack of disclosure by players (Salmon et al. 2021, Cunningham et al. 2021). As professional rugby players may not disclose their concussions, it is incumbent on medical teams and coaching staff to identify abnormalities concerning the players' health during training and competitive matches (Tucker et al. 2021). Exposure to further concussion injury risk or inaccurate on field assessments is known to endanger the player to further injury (Smulligan et al. 2022). There have been open discussions about concerns of medical teams, coaching staff, club owners and player representative bodies regarding the long-term health of current and retired players (Hind et al. 2020). These concerns have been justified based on recent revelations about repetitive head impacts and long-term cognitive and neurological damage to ex-professional players (Suter et al. 2022; Pearce et al. 2018). The purpose of this current research was to gain the players' perspectives on concussion management practices including the collective duty of care from head coaches, coaching staff, medical teams, and owners of professional rugby club franchises.

6.2 Methods

6.2.1 Study design

A reflexive thematic analysis approach was adopted for this research study using the Braun and Clarke methodology (Clarke and Braun, 2015, Braun and Clarke, 2019). A semi-structured interview design was utilised to individually interview the ex-professional male rugby union players (n=23) to ascertain their personal opinions regarding the duty of care that head coaches, coaching staff, medical teams, and club owners had towards professional players. All participants in this study had been employed as professional players and had retired from the game of rugby union within the last 10 years. The format for the interview questions were designed to establish their career as professional rugby players including how their careers commenced, progressed, and ended. Questions on the frequency of career exposure to injury were incorporated along with specific questions related to concussions and physical injury. This in turn would provide their opinions on who was responsible for the duty of care concerning concussion management.

6.2.2 Ethics & procedure

Ethical approval was sanctioned for this study via Research Sub Committee of Galway Mayo Institute of Technology (GMIT; RSC_AC_23062020). The initial number of participants were identified via the lead researcher (ED) by distributing an open request alongside a detailed participant information sheet regarding the purpose of the study. The initial informal discussions were an occasion for the participants to discuss the objectives of the study and how the resulting data would be managed in a strictly confidential manner. Verbal consent was recorded for each participant before their individual interview occurred. As the interviews were semi-structured, the data that were collected from interviews that ranged from 25 - 70 minutes in duration. A standardized series of questions and supporting questions were applied across all the interviews. All information related to the study were fully anonymised to protect the ex-players from identification.

6.2.3 Participants characteristics

The twenty-three male participants who had retired from playing professional rugby union at the time the interviews were facilitated. At the time of data collection, the ages of the players that were interviewed ranged from 29 years old to 43 years old (average age 35.5 ±4.7 years). Participants were interviewed from a wide distribution of countries including both the northern and southern hemispheres to get broad perspective on this topic. The following countries were represented: Ireland (n=17), England (n = 1), Scotland (n = 3) and Australia (n =2). From this group of players (n=23), 14 had represented their national team at full test level rugby union (61%). The mean career duration in professional rugby for the cohort was 9.3 ± 2.7 years and the average age at the time of retirement from the game was 30.8 ± 2.9 years. Concerning the positions that they played during their careers (i.e., 'forwards' and 'backs'), 70% were forwards and 30% were backs. Within these two broad playing divisions, the 'forwards' had a breakdown as follows: front row (n=6), second row (n=2) and backrow (n=8). The 'backs' had the following breakdown, winger (n=2), centres (n=3) and scrum half (n=2).

6.2.4 Sampling and eligibility criteria

For this study, an exponential non-discriminative snowball sampling method was utilised whereby the initial participants who volunteered provided multiple referrals (Biernacki and Waldorf, 1981). Each ex-professional player that volunteered through the referral process was investigated until primary data from sufficient samples were collected and information redundancy was reached (Braun and Clarke, 2021). Participants were informed that they had no obligation to introduce any other potential participants. The interviews recorded a standardised sequence of responses due to the semi-structured nature of the process across the participants. This permitted the research team to identify common themes and responses from the cohort of participants.

6.2.5 Data collection

The replies to the interview questions were used to gather evidence of their personal experiences. These experiences described their position and opinions on how club medical teams, head coaches and owners of professional rugby clubs managed concussion. These personal incidents occurred during their professional careers and included the observed experiences of fellow professional players that they witnessed. This study sought to add the 'player's perspective' to the information that governing bodies and lobby groups discuss in relation to the duty of care involving concussion management and return to play (RTP) protocols. These data provide first-hand accounts which may inform current and future players who participate in rugby union and other contact sports.

6.2.6 Data Analysis

These data were reviewed and analysed thematically according to the Braun and Clarke's (Clarke and Braun, 2015; Braun and Clarke, 2019; Braun and Clarke , 2006) reflexive thematic analysis following an update to their original thematic analysis approach. The research team utilised an established critical realist framework to categorise and ascertain the ex-professional players' descriptions of their experience of concussion management in professional rugby union.

6.2.7 Transcription

The original audio soundtrack of the interviews (via MS Teams) were transcribed verbatim by the lead researcher (ED). These transcripts were examined for exactness compared with the original audio recordings to cross-check and re-edit the transcripts. This procedure involved an initial familiarisation with the content of each transcript by re-reading each transcript on four separate occasions per interviewee. This practice enabled the lead researcher to confirm that the questions and responses interrelated with the audio soundtrack of the interviews. Another member of the research team reviewed all amendments and/or corrections to the final transcripts (LR).

6.2.8 Coding

The coding for this study focused on the semantic meaning of the interview transcripts. This was carried out by the first author (ED) and reviewed with another member of the research team (LR). The codes included the full range (both negative and positive) of concussion management experiences associated with being a professional rugby player. Theme development was guided by the first author (ED) in discussion with another author (LR). Initially duty of care associated with concussion management, return to play protocols and the use of protective equipment were identified as potential themes. Categories were first created to describe the raw data into meaningful units. Subcategories were then developed to denote the shared relationships between categories. The two overarching themes were then identified after further analysis of the sub-themes and their relationships (Table 6.1, page 100).

6.2.9 Researcher background

The primary interviewer for the research was ED. This collective decision made by the research team was based on his previous employment experience of being part of a professional rugby organisation in a coaching role. It was expected that the retired professional players would be more unreserved in their responses when compared to other members of the research team. This approach was supported as it would be a male interviewer (ED) conducting the interviews with male participants.

This was regarded as a positive characteristic with respect to the recruitment of participants for this study.

6.3 Results

Initial descriptive codes were categorised and using further analysis, relationships between the codes were identified. This enabled the development of sub themes which in turn lead to the classification of overarching themes. In this study, two major overarching themes were identified: (1) duty of care to professional rugby players by medical team, coaching staff, and the owners of professional clubs; and (2) the use of protective equipment and law changes to enhance player safety of the field of play. These were based on the identified subcategories and the relationships between these and the subthemes.

Table 6.1 Results of thematic analysis of retired professional male rugby players' perceptions of duty of care towards players and protective measures in the game (n=23)

Themes	Categories	Subcategories	Sample Quote
1. Duty of care to players to players by medical personnel, coaches, and professional clubs	Medical interventions	Influence of medics on concussion diagnosis and intervention	"…. they took me off the pitch so you know you're relying on really, really good medical help to step in when you're not fully with it." (P4)
		Strong personalities in the medical team, knowledgeable, under pressure to manage, lack of experience	"Any medical staff that I worked with and are always really on top of it in that respect and there's no dressing down the severity or the potential severity that concussions can have." (P18)
		Lack of resources or experience	"They were very stretched so that was probably a pitfall. I think if I potentially have been looked after a little bit better, my career would went on longer." (P5)
	Concussion testing and return to play (RTP) protocols	Improving testing, not robust enough, subjective testing	"The concussion protocols you go in and you do the test with the playing cards and all that kind of stuff, I passed them (while symptomatic)." (P22)
		Setting lower baseline tests, intentionally scoring lower	"I remember actively practicing those tests, trying to figure out the months of the year backwards learning that so I could do it. I could go into autopilot and beat those tests…….you can beat the system." (P15)
	Coaching staff and head coach	Influence of coaches on medical staff decisions and player readiness	"No definitely not, and not every player was as honest, some players were more honest and not

			every coach was happy for the medical staff to make the decision.” (P8)
		Players coaxed to play or no pressure from coaches	“there are situations where you have an overbearing coach and maybe not as strong of a personality in charge of medical and the player does not get forced back, but coaxed back into playing.” (P14)
	Role of the professional rugby club owners	Sustainable business operations	“if you're going to run a sports team, you've got to be responsible for your employees. it's the same as any business you any well-run business, uh, as empathy towards its employees and wants the best for them. (P14)
		Duty of care and long-term duty of care	“but like there is going to be a lot of broken men coming out of rugby, that's just the facts I think, and they probably do need a lot more support than they have at the moment (P15).
2. Use of protective equipment and law changes to enhance player safety on the field of play	Attitudes towards protective equipment for players	Use of protective equipment (scrum caps and gum shields)	“I don't think scrum caps themselves can have much of an effect, I think it may help with pain of head collisions and obviously with cuts and everything else and to avoid getting split.” (P18)
		Reckless behaviour	“Deliberately took it off because he thought he was more cavalier and reckless with it on (scrum cap).” (P16)
	Improving on field safety for players	Tackle technique	“We can coach our young athletes in in their tackle technique as well, I think will be a would be a big defining factor.” (P2)

	Strength training and neck strength	“I think exercise, probably neck strengthening…but I don't think any head gear or gum shields are going to help you.” (P9)
	Law changes in contact areas	“Players flying into rucks and taking lads heads off, that's probably something that could be looked at 'cause it is quite dangerous.” (P5)
	Reducing tackle height	“There aren't many rules that you can change that are going to protect the tackler.” (P14)

6.3.1 Theme 1 - The duty of care to professional rugby players by medical personnel, coaches, and professional clubs

Medical Interventions

The retired players had relatively consistent opinions regarding their personal experiences with medical teams within the professional clubs by whom they were employed. In many instances, the level of knowledge about concussion which the club doctor possessed was viewed as being central to the recognition and management of on field concussion incidences. For example, "…*any medical staff that I worked with are always really on top of it (concussion) in that respect and there's no dressing down the severity or the potential severity that concussion*" (P18) and "…*I feel like the medics, know the risks are so great with concussion, I suppose that they take a pretty hard line on it, and rightly so*" (P2).

The caveat to these opinions would be the level of experience that the medical teams possessed, whereby less experienced personnel may be swayed by the players themselves or members of coaching staff. This point was illustrated by *"I guess it's the fact that the matter is that with concussions are still quite an unknown entity and medical teams do their best*" (P12) or *"I do not remember the first 20 minutes of that game I remember being on the side-line and the doctor talking to me and I'm wondering why he was talking to me*" (P11). Difficulties arose were there were instances of more subtle concussion symptoms: "…*those were the probably the trickier ones to diagnose because you know while you have a physio there, and you know and, at the same time your physio, and that's not their job (to diagnose concussion*)" (P11). Some players had a more severe perspective on concussion management during their playing careers: "*Hindsight is easy at this point, isn't it? To look back and say how disgraceful it was (recognition and management of concussions), but it was just the way things were done*" (P5).

An overriding perspective that was discussed was the strength of character of the lead medical resource or the lead physiotherapist. Many players agreed that the medical team generally had the best interests of the players foremost in their actions. This protection of the players by the medical team not to be influenced by coaching staff was admirable "*I think for the time that I was under their care, I've never worked with a medical team that doesn't care about their players*" (P12). With reference to medical staff that buffered coaching staff "*I was lucky that medical staff I worked with were always strong enough personalities*" (P14) supported by "*So she (the doctor) had the respect (of the head coach / coaching staff) that she could make a comment on what was happening in the moment, and no one would argue"* (P16).

Concussion testing and return to play (RTP) protocols

It was the contention of most of the participants that concussion testing and RTP protocols were not robust enough to fully detect and manage concussions. While none of the participants were medically qualified, they felt able to manipulate the RTP system *"... (if you failed a test), you'd say nothing about it because you got another one (from the physiotherapist) the testing on the computers, that was a bit of a joke"* (P13). In addition, this point was expanded upon by another participant who stated that *"The concussion protocols you go in and you do the test with the playing cards and all that kind of stuff, I passed them (while symptomatic)"* (P22). The ability to manipulate test results may have had more serious consequences as one participant noted that *"...it (concussion diagnostic procedure) was definitely not a robust process because I passed (while being concussed) it and then was able to just say jump in my car and drive home"* (P23).

A notable comment was that RTP protocols may have been influenced by the comments the players made to the medical team regarding their recovery. These circumstances were exacerbated by players not fully disclosing the extent of their symptoms as they were progressing through the RTP protocol *"I remember going back jogging and in the early stages in the protocol and like even just that movement of a light jog was like I just felt woozy (and said nothing)"* (P6) and *"I remember the first training session back, I ended up getting sick (undisclosed) which you know is obviously a massive red flag"* (P6).

This occurred on multiple occasions particularly where the on-field doctor or physiotherapist was less experienced or less forceful in their stance to remove the player *"…. the (physiotherapist) came with a bottle and told me 'Look, I think you need to come off' and I'm telling the physio, no I'm fine"* (P8). The RTP protocols are widely accepted as most the established pathway for players to return to play after a suspected concussive incident. Many players expressed comments of concern regarding the accelerated RTP procedures that professional rugby players utilise. Even though recent changes (World Rugby 2022) to the duration of 'stand down' time post concussive injury for a player has increased to twelve days, some players at the time of data collection felt that this may not be adequate:

"I can get knocked out on a Saturday and if he starts his RTP on a Sunday with no symptoms, then he can play again the following Saturday and I don't think that that's right. Like I mean, I think if a guy has visibly been visibly lost consciousness or has come close to losing consciousness, I don't see how it's acceptable that he's back on the field seven days later if we're being serious about it" (P18).

As illustrated by the former players' comments, the existing RTP protocols were not robust enough to ensure that their personal recovery was being managed thoroughly. Even though they were proceeding per the parameters of the RTP protocols, many players were not recovering within the specified RTP timeframe. Some players were enduring ongoing symptoms as they advanced through the protocols prior to returning to play:

"I remember about four five days later (going through RTP protocols) I was leaving the facility and I walked out the front door and I just had no memory of where I parked the car. You know I'm just standing there for a second and I think that unsettled to me" (P11).

This was a common occurrence with the current RTP protocols at the time of gathering these data. Many players experienced 'dark room syndrome' in an effort to recover quickly and become available for selection within the allocated RTP recovery period: *"I know a couple of them (fellow professional players) have literally been locked in dark rooms for two weeks*" (P14) and *"I'd go through periods (during RTP) particularly towards the end of the day as I was getting mentally fatigued where I need to go to the room and have a lie down"* (P12).

The concluding messages from the ex-players were that the RTP process needs to be *"taken out of the players hands"*. In this respect, they meant that the player should not have any influence over their recovery. The RTP process needs to be monitored by club medical teams and independent medics not associated with the rugby club. This may be facilitated by implementing a more impartial RTP system that is comprehensive, independent, and fully objective:

"There's no (longitudinal) evidence to suggest that the current way in its current format actually gives clarity around whether a concussion is taking place or not. I would like to see further investigation into the merits of it because I think something like that takes the subjectivity out of it and makes everything as objective as possible". (P17)

Coaching staff and head coach

As professional rugby union clubs are a result driven business, it must be understood that head coaches and coaching staff are contractually driven to deliver winning match results. In this respect, coaches aimed to achieve these outcomes by utilising the roster of players at their disposal to win matches. As has now been established, many players chose to play while physically injured or while being concussed. During the ex-player interviews, there was a broad spectrum of opinion about the influence or pressure applied by head coaches and coaching staff on players to compete while being either physically injured or remaining symptomatic with concussion. This is illustrated by the extremes of opinion: *"There's never any pressure from coaches to stay on the pitch"* (P12) to *"There used to be a lot of pressure coming from the coaches to get back out onto the field"* (P16).

Many players explained that they experienced pressure to play while being symptomatic as demonstrated by the following comments:

"But as you know there are situations where you have an overbearing coach. There may not be a strong personality in charge of medical and the coach gets what he wants, and you do hear stories of players getting forced back into playing, not forced back, but coaxed back into playing" (P14).

This was further illustrated by head coaches or coaching staff coaxing players to continue to play *"…you know you being used to people (coaches) telling you like there's nothing wrong. It's nothing to worry about, you know"* (P21). On occasion, the overbearing influence of coaches may not have aligned with what is best for the long-term health of the player. The main reason for this is that the coaches were under pressure to produce winning results.

"When I notice as a player you are paid by the club to play there's pressures on the director of rugby too because of relegation playoffs, to make the top six et cetera. Then your medical staff is basically subservient, they have to keep him happy" (P 9).

Some players acknowledged that the coaching ethos they experienced evolved over time, whereby some felt that *"I feel when I was younger (player); there was a bit of negligence from coaches and the general conversation around concussion"* (P5). This 'win at all costs' ethos of "*They're making decisions based on the business of winning games*" (P8) was replaced in many instances. The evolution of coaches moving from overbearing to accepting the opinions of the medical staff with regards the health status of the players was evident: *"I see a much greater awareness of the symptoms of concussion, the dangers, the concussion, the return to play protocol as they are far better adhered to…. it's much safer"* (P6). This transition of coaching ethos may not always be done willingly, however:

"*Sometimes you get the case of coach little bit old school, and he has, maybe have a few gripes about it, but ultimately, I think they know that it's for the for the right reasons; you know that they want their best players available"* (P17).

As the ex-players expressed on numerous occasions, professional rugby union is a business and as such, they were acutely aware that the head coach and coaching staff were ultimately reporting to club owners and shareholders. This created pressures on the coaches and coaching staff as their careers and contracts were dependant on attaining results in competitions *"I think players need to feel comfortable that they're not getting pressured to play, which is easier said than done because more often than not, it's the coaches or the owners put pressure on"* (P14).

Role of the professional rugby club owners

Intrinsic to the success of professional rugby clubs are the investors or outright owners of the clubs themselves. In many respects, the careers and contracts of the head coaches, coaching team, medical teams, and players are dependent on the patronage of the club owners. The ex-players interviewed for this current study were acutely aware of the authority of the club owners. This was expressed as a 'hand in glove' approach where the head coach or director of rugby was essentially the day-to-day representation of the club owners: *"Because of all the external pressures because of those sub conscious agendas (implemented by the head coach) everybody has a boss"* (P21). The ex-players were employees of the club, however some expressed concerns over the volume of games they had to play during a season:

"…there certainly has to be a little more regard for what actually serves the best interests of the players. Rather than just let lumping more games on top of them and squeezing the cash cow for a little bit more" (P1).

This manifested as a clear understanding that owners had to sell tickets and provide entertainment for the club supporters to support their rugby club business: "*They're dependent on a crowd coming in the gates and on entertainment…. that's going to make it the best rugby experience on the weekend"* (P8). The was a pervading sense from the ex-players that the club owners dictated the club culture. Some of the ex-players had very positive experiences with some of the professional clubs based on how the club was operated by the club owners:

"So, it's kind of building the trust and building a good culture (in the club). The best teams I played with you didn't have any of that sort of unknown uncertainty (unstable contracts), it's probably likely going to lead to better performance anyway" (P16).

When players were traded when their contracts ended, sometimes resulted in them being uncertain in terms of how a new employer (club) viewed player welfare. The ex-players were clear in relation to how they discussed a potential move to a new club:

"You go to different places where players are seen as assets in one place and they're not in another club. You have owners that want to make the money at all costs, and you have owners that want to do it as best they can" (P8).

This was further supported by comments such as *"You know, if you had an offer from certain clubs and an offer from another club with a bad reputation (on managing player welfare), I think a lot of players that would choose to go to (a club with a better reputation)"* (P12).The predominant reason for joining a new club was influenced by perceptions of how well they (clubs) managed players whether they were injured or not. It was the broadly accepted opinion by the ex-players that the club owners have a duty of care to the players, while they are representing the club and post retirement:

"They (club owners) should care for them when they're there, and if something happens, care for them in the future. I certainly think it's part of any organization, any sport or any business, they should be able to look after their people and part of that would be warning about the current side effects or potential side effects (of repeated concussions or sub concussive impacts" (P7).

Most players stated that club owners "*have a duty of care to the players*" and these types of insights were reinforced by players stating that:

"Absolutely they have responsibility. I think if you're going to own a sports team, if you're going to run a sports team, you've got to be responsible for your employees. It's the same as any business or well-run business, it has empathy towards its employees and wants the best for them (in the long term)" (P14).

The ex-players were adamant that the long-term health of themselves and their fellow retired professional goes beyond the playing contracts. It needs to be extended into the retirement phase of their lives as many professional rugby players retire relatively early due to the highly attritional nature of professional rugby union. These views are relevant as many ex-professional players retire with physical injury and with long term mental health issues, *"It's in your mental health, really. That is maybe where there's a bit of a discrepancy...like I do think that first year or two when you finish, a player can really struggle"* (P20) *or "(I'd be) driving down a gravel road and remember a few times, trying to drive as slow as possible because the shaking of the car (blurring effects on vision)* (P20). This point was supported by the necessity to provide resources for players that may be experiencing the effects of physical injury or mental health difficulties post retirement:

"There should be a certain amount of money or whatever resource is towards. I think this is probably something that might crop up in the next 10 years......put money towards like a scheme which does help players who are really struggling" (P14).

The consensus from the ex-players related to the duty of care from club owners post retirement was a level of relatively simple support. The suggestions were for example, ongoing access to club physiotherapists or specialist doctors associated with the clubs. The principal reason for this was illustrated as follows:

"…. but like there is going to be a lot of broken men coming out of rugby, that's just the facts I think, and they probably do need a lot more support than they have at the moment. I think there does always

need to be a safety net for those players, especially when you leave the game and you're used to a certain level of care" (P15).

6.3.2 Theme 2 - Use of protective equipment and law changes to enhance player safety on the field of play.

Attitudes towards protective equipment for players

All the ex-players had worn various types of protective equipment throughout their playing careers. These included shin pads, shoulder padding, protective equipment for the groin, hand protectors or padding round the hip area. By far the most used pieces of equipment were scrum caps (to protect their heads) and gumshields (to protect their teeth and mouth). Most players had worn either a scrum cap or a gumshield or a combination of both while playing professionally.

One player stated that a *"…. to a certain extent, especially a well-made, well-constructed modern gumshield will really help lower the risk of getting certain concussions"* (P7). However, this was not a broadly accepted opinion by most of the ex-players. Other players declined the use of gumshields as they found them difficult to use in terms of breathing. One player was wearing a gumshield and *"…had teeth knocked out with gum shield then as well"* (P5). The general opinion for gumshield use across the cohort of ex-players was that it was a personal choice. When a player had a large impact to the mouth or jaw area, the gumshield would not mitigate against concussion or concussion risk: *"I can't see I don't think any head gear or gum shields are gonna help you"* (P9).

The views on scum caps were more clearly defined by the group of ex-players: *"Most guys are of the opinion that scrum caps themselves don't actually mitigate concussion in any way, shape, or form"* (P18). Other players described them as *"placebos"* (P6, P15, P22) or when they were wearing a scrum cap *"I did clash with (players) who were wearing scrum caps and they generally always came off worse"* (P1). Further inquiry clarified that most chose to wear some form of head protection in order to reduce abrasions to the skin or stop further cuts if they were protecting an existing injury *"…so they're really only good for cuts and abrasions; they 'don't serve any purpose (in protecting against concussion)"* (P1) and *"it (scrum cap) was more after splitting my head open, I think and then having swollen ears"* (P6). The ex-players were sceptical in relation to scrum caps in mitigating the effects of concussive or sub concussive impacts. In this regard, the ex-players had well established opinions: *"because they don't stop your brain rattling around inside your head"* and *"I've heard a lot about is this is the action of your brain inside your skull rather than impacts on the outside"* (P5) or *"get the impact going one direction and the impact sends him another direction and it's actually not them hitting the ground. It's the movement of their head at that speed"* (P6).

This broadly held position that scrum caps could not prevent a player's brain from moving once impacts and collisions were experienced during a match provided a key insight. Conversely, some players believed that by wearing a scrum cap, it made them more cavalier during rugby matches: *"I'd be inclined to think if you're wearing a scrum cap, you're actually more inclined to be a little bit more aggressive, you might go into things a bit harder*" (P3). Some ex-players used the word 'reckless' in relation to players wearing head protection. It led players to believe that they had a greater sense of safety: *"…and then you've got people saying that actually they encourage players to have an over sense of protection"* (P17) *or "I deliberately took it (scrum cap) off because he thought he was more cavalier and reckless with it on"* (P16). The overall sentiments on the use of scrum caps in professional rugby was exemplified by:

"…. You get this feeling of invincibility (wearing a scrum cap) and they (professional players) do tackle with their heads (and are) taught to tackle with their heads, which is just mind blowing in this day and age. It does in fact increase the extra risks they are taking, and it doesn't stop anything in terms of the speed of the brain hitting the inside the skull" (P14).

Improving on field safety for players

As rugby is a contact sport, there are specific playing positions on the field such as outside centre or back row players that are subject to high levels of physical contact throughout a game. This can naturally lead to some players being more exposed to injury risk than their teammates. Other aspects of the game carry an equally high risk of injury, for example tackling, scrummaging, rucks and mauls. Most players throughout the course of a game will be involved in these high impact and potentially high injury risk situations. In recent times, World Rugby have attempted to address the level of injury risk exposure that players have during these contact situations by amending tackle height amongst other measures (Tierney and Simms, 2018).

As previously mentioned, many players believed that fewer matches throughout a season would reduce injury risk. This was supported by other players suggesting that less contact (e.g., tacking, scrummaging, rucks etc) during training sessions would further assist in reducing injury risk exposure: *"The game at the moment is basically just designed around being a bigger, stronger player… it's just to be massive, powerful people running into each other… it doesn't always have to be this massive collision thing"* (P15).

One aspect that World Rugby cannot influence is the ongoing ethos of developing larger players that will ultimately engage in larger collisions. This trend of developing a larger physical specimen of player reflects the current state of the game of rugby union. With more physically developed athletes competing, translates into less space on the field of play and a higher injury risk. One player succinctly stated that *"rugby is coached around not conceding ground, so you're kind of looking for big aggressive front on hits (tackles) all the time"* (P1).

When players are larger, one element of the game may be addressed to combat physical size with better contact skills in the collision areas of the game. This opinion was supported by ex-players who felt that an improvement in tackle technique would reduce concussion incidence in the tackle area: *"…I think you can improve around the tackle area by just coaching people, be better on how to tackle"* (P21). There were other suggestions that may mitigate against concussion around the tackle area by limiting the number of players involved:

"…. if you can execute a far better tackle, in a more efficient (manner), it's more likely to mean that you actually need less people to tackle. When you get that sort of multi-person tackle… it is gonna cause more concern when you got three or four players (in a tackle) … you are just increasing the chances of concussion" (P16).

Recent research found that reducing the tackle height may reduce the frequency that rugby players receive an impact to their head or neck region. This research concluded that lowering tackle height resulted in an increase in concussions compared to standard tackle height (Tierney and Simms, 2018)). In the participants for the current study, there were a variety of opinions related to the discussion of 'tackle height'. Some ex-players stated that law changes may have little or no effect: *"He's (tackler) gonna get clipped by a hip or a knee or whatever and you lose your line of vision the lower you go"* (P5). Another shared such a view by stating:

"Lowering the tackle height further, which has been discussed, would be a mistake. I think that if you were to make everyone tackle below the waist, I think that's going to lead to more concussions. Because the reality is for someone who is 6'6", if you got to defend two players and all of a sudden, you make a last second decision (to make a tackle below the waist); it's my head is the thing that's gonna take the bang (and get concussed)" (P14).

The final consensus regarding tackling in the game was that there is no simple remedy to reduce the current rate of concussion in professional rugby union involving the person who instigates that tackle *"it is very difficult to change (how to tackle) …. There aren't many laws that you can change that are going to protect the tackler…. or the ball carrier"* (P14). This will continue to be the status quo of professional rugby union as in many ex-players opinions, the reality is that:

"The game has become even tougher because people are adapting to it, but they're still getting bigger and stronger, you know, and the collisions are still getting bigger and stronger; the games are not getting softer" (P17).

As mentioned, tackling is an area that generates most concussive incidents in the game (Cross et al. 2019). However, there are other contact areas that involve a combination of tackling and general physical strength such as scrummaging, mauling and rucks. With many professional rugby union teams aiming to play a high tempo style of play to retain possession, rucks are a high-risk injury area in the game (Paul et al. 2022). Rucks and rucking involve high speed collisions to 'clean out' opposition players. This translates into highly athletic players accelerating into impacts using a large amount ofp physical strength and force to remove opposing players which translates to an increase in injury risk (Williams et al. 2021) .

One ex-player that had experienced multiple concussions throughout his career stated that *"… most of mine (concussions) came from cleaning out aggressively or getting cleaned out 'cause you end up on your back*" (P21) which translates to players being in vulnerable positions and exposed to additional injury risk. This area of the game is difficult to monitor because of the number of variables that happen during rucks in the game of rugby union. World Rugby have attempted to change the laws of the game relating to rucks and the 'breakdown'. Some ex-players believed these law changes did not mitigate against concussion or other injury risk *"but whenever you step back and see the way the game is gone, since these laws were introduced, some people ask, 'has it become safer?' no, it hasn't"* (P17). Alternatively other ex-players suggested that strength coaches could mitigate against concussion risk by developing neck strength in their players, *"amount of posterior work around the neck within their program as a prevention strategy"* (P3) or "*I think exercise, probably neck strengthening and I don't know enough about it, could possibly help reduce concussion"* (P9). These comments regarding neck strength were at odds with other statements about the mechanism of how the brain moves within the skull once a player is tackled or involved in other contact areas of the game.

6.4 Discussion

This study sought to understand the players' perspective in relation to their personal experiences of concussion and how these were dealt with by the medical teams, head coaches (directors of rugby), support coaching staff and professional ruby union clubs. As mentioned previously, all participants in this study had played professionally for several seasons and all had experienced multiple concussions throughout their careers. In addition, the participants had witnessed many fellow professionals experience concussions during their careers and the long-term effects of concussion.

A consistent factor that emerged was that an experienced, well-respected medical lead was essential in any professional rugby union organisation. This was viewed as important for an obvious reason i.e., a higher level of concussion knowledge and management experience may translate into a better level of care. A secondary reason was that a well-respected medical lead was a key component to act as a buffer between the players and coaching staff (including the head coach). It was evident during these interviews that players were coerced to return to play sooner, rather than be given adequate time to recover post-concussion. This is propelled by the certainty that professional rugby union franchises are results driven and financially focused businesses. Head coaches, coaching staff, medical staff are employed by professional rugby organisations to deliver results to club owners and investors.

As has been reported previously in the literature, medical staff are generally seen as having the highest level of concussion knowledge and are encouraged to play the significant part in providing concussion awareness and education (Mathema et al. 2016). Even though this is generally accepted as the case, it remains challenging for medical staff to translate concussion knowledge for coaches, coaching staff and players (Yeo et al. 2020). Due to a discrepancy in understanding of the mechanism and severity of concussion, it has been reported that many players and coaches did not believe that concussion can impair performance (Mathema et al. 2016). As has been recorded in the literature, coaches can pressurise medical staff to clear players to play and manipulate the RTP process (Rosenbloom et al. 2021, Montgomery et al. 2018). Where medical staff and clinicians are reported to have pressurised players to return prematurely, this type of practice will only further compromise the long-term health of the players in many facets. It is imperative that medical teams adhere to robust objective RTP protocols for the long-term health and wellbeing of the athletes under their supervision (Pearce et al. 2021). Players who have a history of concussion are twice as likely to experience other forms of physical injury compared to players who do not have a history of concussion (Hunzinger et al. 2021).

As professional rugby clubs are established to be viable commercial businesses, it is paramount that they operate in an ethical manner (Mc Leod and Nite, 2019) . Professional rugby clubs are unique due to the attritional nature of the sport. Simply expressed, this means that club owners and club administrators are required to properly manage the interests of their players first (Ranaweera et al. 2022). Previous research into this area has suggested that players view themselves as ‘commodities and that injury was viewed as an ‘occupational hazard’ within rugby union (Daly et al. 2022). Many of the players interviewed for this current study, believed that appropriate contract management, club culture and having their long-term health needs considered are basic tenets for a well-managed professional club.

While they were competitive athletes, the most effective tool to protect the players from undue exposure to injury risk was by managing workload. From this perspective, all stakeholders involved in running professional rugby clubs need to manage the physical demands that players are exposed to over the course of their careers (West et al. 2020). This spectrum of player responsibility includes head coaches, coaching staff, medical teams, and professional club owners.

Emerging evidence has found that many ex-professional rugby union players are experiencing long term physical injury, and long-term cognitive damage as a result of playing the game professionally (Hind et al. 2020; Owens et al. 2021). All participants in this current study had multiple concussions (diagnosed and undiagnosed) throughout their professional playing careers. Research by Rafferty et al. which focused on professional rugby union highlighted that players were more likely to be concussed than not concussed after 25 competitive matches (7.9 [95% CI 5.1 to 11.7] to 21.5 injuries/1000 player-match-hours [95% CI 16.4 to 27.6]) over the duration of four playing seasons). This research also found that after suffering a concussion, players had a 38% greater injury risk for another concussion compared with a non-concussive injury (Rafferty et al.2019). Comprehensive responsibility by club owners, head coaches, coaching teams and medical teams must be viewed as essential to managing player workload for long term health even in retirement. Furthermore, part of a player’s consideration during contract negotiations is how they perceive player welfare issues are being managed within a club. Exhibiting a high level of player welfare and long-term duty of care policies could have an impact on a club’s ability to recruit prospective players.

Most players interviewed had used protective equipment during their playing days. The overriding opinion by the participants was that these types of products did not mitigate against concussive impacts either while training or while playing competitive matches. There is strong evidence to support the players opinions. For example, research by Stokes et al. (2021) found that scrum caps did not reduce the odds reducing concussion in professional rugby union (adjusted odds ratio=1.05, 95% CI: 0.71–1.56). There are many misconceptions about the protective merits of wearing scrum caps. For example, in contrast to the intended purpose of encouraging players to play in a safer manner, scrum caps can induce players to play more aggressively (Knight et al. 2021). These points were mentioned by the participants in this study as they used words like ‘reckless’ and ‘cavalier’ when discussing scrum caps. This suggests that greater evidence needs to be provided via longitudinal studies regarding the effectiveness of scrum caps on concussion mitigation. Currently many scum caps claim to reduce linear or rotational forces to the scum cap itself, however these research papers do not prove that this prevents the brain from moving within the cranium of the player (Draper et al. 2021).

Since 2019, World Rugby have made attempts to alter player behaviour in relation to tackle height and more specifically high tackles. With the introduction of the high tackle sanction framework (HTSF), there was a notable increase in high tackle sanctions (58%) but a visible improvement in player behaviour regarding height tackles was not observed (Raferty et al. 2021). Strict adherence by referees to the laws of tackle height and adaptation by head coaches and coaching staff are required to reinforce this necessary change in player behaviour (Raferty et al. 2021) .

Other experts in the area of tackle technique have proposed that either reducing the speed of entry to contact situations like tackling and rucks may reduce the odds of injury risk (Cross et al. 2019). Tackles to the torso and chest areas of players has been viewed as a successful way to defend against offloading by the ball carrier. This practice can lead to an increase in head-on-head contact between defenders and attackers (Amayo and Tierney, 2021) . When players are coached to tackle lower, there will be an increase in offloads, but this may translate to safer tackle techniques for the defender and the ball carrier, this lower tackling may assist in changing player behaviour with respect to tackling (Amayo and Tierney, 2021) .

6.5.1 Limitations and conclusion

Professional rugby union is a highly physically demanding field sport. It is imperative that those who are responsible for the long-term welfare of the athletes who play the game, do so in a holistic manner that protects the players. Many of the players who were interviewed for this study, stated that all decisions about RTP should be taken out of the players hands and the need for the implementation of a more stringent concussion testing protocol. In addition to this, many ex-players would prefer a longer RTP process. Professional players will not disclose injury for a variety of reasons as they are highly competitive individuals who want to retain or obtain lucrative playing contracts. In turn, the long-term health of players must be monitored by medical staff, coaching staff, head coaches and club administrators. There is mounting evidence to suggest that there are long term effects of repetitive head impacts, leading to detrimental effects in cognitive abilities and neurological health of current and past players.

It is reasonable to say that players need to be protected in terms of workload management and from themselves. A fuller understanding of head kinematics and/or tackle height would be beneficial along with an adjustment of player behaviour in the contact areas of the game. These may assist in reducing the incidence of concussion or injury risk in rugby union. Other approaches to a making the game safer may be derived from different coaching practices centred on the ball carrier's responsibility in the tackle situation. There are limitations to the current study as the cohort had retired in the past ten years. During this time, there have been changes and recommendations to the laws of the game and to the level of workload experienced by existing rugby union professionals. These changes may have an impact on long term injury issues for future professional players.

Finally, as described by the players themselves, further work by professional clubs to ensure the highest duty of care is delivered not only to currently listed players, but also recently retired players, to ensure that those who have contributed so much to the sport's growth and success, remained protected.

Post Publication Reflection

Alternate suggestion for text:

The line 'Previous research into this area has suggested that players view themselves as 'commodities and that injury was viewed as an 'occupational hazard' within rugby union (Daly et al. 2022).' Should be changed to 'As part of these interviews (published previously Daly et al. 2022) players suggested that they viewed themselves as 'commodities and that injury was viewed as an 'occupational hazard' within rugby union.'

Chapter 7 - Evaluating the relationship between neurological function, neuromuscular fatigue, and subjective performance measures in professional rugby players.

Preamble

Many injury aetiology models suggest that prior or current injury may expose players to a greater injury risk. Consequently, there are numerous prospective predictive measurements utilised to reduce injury risk in contact and collision sports. These prospective player workload management modalities are utilised across many levels of professional and amateur rugby union. Injury risk is inherent in contact and collision sport due to the physicality of the games being played. Consequently, reducing injury risk exposure is a complex matter due to the multifactorial nature of injury risks in these types of sport. One of the more common modalities of player monitoring used by practitioners (i.e., performance coaching staff) is the use of internal and external workload measures for player preparation. This study aims to compare three different readiness to train measurements (one subjective and two objective) within a cohort of senior professional rugby union players. The rationale for this study is based on existing aetiology models where injury risk can be categorised into modifiable and non-modifiable injury risk factors (Windt and Gabbett, 2017). Examples of modifiable and non-modifiable injury factors are components like fatigue, exposure to injury inciting events and individual player workload. When coaches monitor and manage workload for athletes, it is understood that this will either impact negatively or positively on the athlete depending on the overall management of workload. This study used subjective data (POMS – profile of mood states) provided from the players, objective data from provided by the strength and conditioning coaches (CMJ - countermovement movement jumps) and neurological measurements using brainwave detection (DC potentials) using the device *Omegawave*.

Publication citation:

Daly E, Pearce AJ, Esser P, Ryan L. Evaluating the relationship between neurological function, neuromuscular fatigue, and subjective performance measures in professional rugby union players. *Frontiers in Sports and Active Living. 2022:438.* https://doi.org/10.3389/fspor.2022.1058326

7.1 Introduction

Managing the health and wellbeing of full-time professional athletes is a time consuming and difficult task to achieve. In high performance, medical staff, sports scientists, and strength and conditioning coaches are continually seeking improved methods to monitor the health of their players and what injury risk they may be exposed to due to prior injury, training methods, time of the season and workload management. As rugby union has been a professional sport since 1995 the importance of player monitoring and tracking is paramount for clubs to remain competitive and retain a full roster of available players as the season evolves.

A significant component of monitoring player health and readiness is determining the workload tolerance of players are before and after training sessions, and competitive fixtures in league or championship (Fuller et al. 2016). Sport scientists are constantly seeking new and more reliable methods to maintain players optimally. The monitoring of workload in players can offer coaches the means to optimise performance in training and in competitive periods during the season. This can manifest in various manners, for example being in a fatigued state will affect a player's ability to perform fundamental components of the game like tackling an opponent (Davidow et al. 2020). Consequently, monitoring player workload around times where playing demands and injury risk is prevalent is a high priority in professional organisations (Cross et al. 2016). This cumulative workload will diminish the ability of the player to perform at an optimal level, result in a performance decrement and expose the players to injury risk.

In professional rugby organisations, multiple strategies are implemented to measure the overall functional state of readiness of players. Many professional sports teams will design preparatory programmes to elicit the required training load stresses for competing at an elite level. In general terms, these are divided into external loads applied and the internal stress measures as experienced by the players. The challenge to many practitioners is to gather and interpret these loads and stresses in a cogent manner that maintains player health and wellbeing.

When examining subjective or objective 'readiness to train' markers, the practitioner is assessing an athlete's response to training. It is now well established that this is a multi-factorial approach, and it is highly recommended that multiple measures are considered to assess an athlete's 'readiness to train' or reduce injury risk (Boullosa et al. 2020). A common measure to monitor external training load used by strength and conditioning practitioners are variants of the reactive strength index (RSI). RSI is a measure of lower body power and can be used a measure of fatigue related to external training load (Heishman et al. 2018). RSI using drop jump, or the reactive strength index modified (RSImod) using countermovement jumps are accepted methods that were primarily developed to demonstrate how athletes manage while performing various plyometric exercises (Flanagan and Comyns, 2008). RSI using drop jumps are calculated as the ratio between jump height and ground contact time, while RSImod is calculated as a ratio between jump height and jump time. As mentioned, the monitoring of RSI variants can demonstrate improvement in athletic performance movement patterns and may be included as factor in determining an athletes' injury risk profile (Flanagan, 2016).

Self-report measures can be provided by the playing cohort in the form of profile of mood state (POMS) questionnaires. Concerns have been that self-reporting may not reflect accurate fatigue levels in players and more objective measures may provide more accurate data about the players (Twist et al. 2012). Further, compliance by players to completing POMS data may not be a sufficient measure of wellness in athletes and may be enhanced by using additional objective measures (Fields et al. 2021). Developing objective test protocols for measuring internal stress levels that players will experience in training or fixtures can be achieved using alternative invasive methods. Such as hormonal biomarkers to determine fatigue levels and/or state of readiness in conjunction that can be correlated with session data gathered by coaches (Caetano et al. 2017). Many coaches and players will opt for non-invasive data gathering methods due to time, inconvenience and expense associated with biomarker data reference points. In this study, the method of gathering non-invasive player data was via *Omegawave*, Espoo, Finland (OW). This technology can monitor biopotential brainwave activity and is well established in the literature, dating to 1875, with the recording of bioelectrical activity in animal cerebral cortex studies (Haas, 2003, Kovac et al. 2018).

It has been suggested that the measurement of biopotentials (DC potential) could estimate the overall functional state of the central nervous system (CNS) (Peterson, 2018) As this method is non-invasive approach that may detect variations in the biopotentials of cortical tissue. These variations in CNS states, for example fatigue, could detect possible alterations in an athlete's overall functional state (Peterson, 2018) . These measurements allow for non-invasive data gathering to assess recovery, overall player readiness and indicators of fatigue that may impede optimal performance. The OW technology uses proprietary algorithms that categorises DC potential of brain biopotentials within a frequency range lower than the EEG range (0–0.5 Hz). The technology uses a proprietary algorithm which generates DC potential measures. These measures include DC potential curve shape (45 mV and higher), a DC stabilisation point (1–3 minutes of initiating the test protocol) and DC stabilisation time. The algorithm generates arbitrary units (AU) on a 1-7 scale for overall CNS readiness with higher values suggesting a higher level of activation of the CNS. Where the values are lower, this suggests that the athlete may not have recovered from previous training session stresses. These relatively uncomplicated scales (1-7) generate overall readiness measures which utilise DC potentials (curve, point, time) and heart rate variability (HRV). Previous research has utilised CNS readiness scores as an effective tool for monitoring athletic performance in elite athletes (Heishman et al. 2018).

The primary aim of this case series in professional rugby was to compare the efficacy of objective DC potentials measurements, neuromuscular fatigue data (RSImod) and POMS questionnaires as a multifactorial means of monitoring player load and state of readiness. Combining DC potentials as a novel measurement approach (i.e., stabilisation point, stabilisation time) in tandem with external player load (RSImod) and POMS data could result in a multifactorial approach to monitor player readiness to train or perform.

7.2 Materials and Methods

7.2.1 Participants

Eleven senior male professional rugby players with a mean stature (±SD) of 185.2 ± 8.6 cm, mass of 101.1 ± 12.9 kg, and age of 27.1 ± 2.1 years took part in the study. Participant information sheets were distributed, and all participants provided voluntary informed consent prior to commencement of the study. The cohort of players were senior professional rugby players who were competing in the domestic league and European champions cup competition during the data collection period. In parallel with this, all players were involved with squad training sessions including strength & conditioning, recovery, and unit skills sessions.

7.2.2 Ethics & eligibility criteria

Ethical approval was received for this study via the Research Sub Committee of Galway Mayo Institute of Technology (GMIT_RSC_AC_201020_CR). Permission was granted by the Irish Rugby Football Union (IRFU) for the collection of data generated and for data supplied by the medical staff and coaches. Signed participant information forms were collected from each participant. It was established that all information would be treated as confidential and anonymised.

7.2.3 Study design

For the purposes of this study, DC potential parameters (range from 0 to 0.5 Hz) were recorded using two recommended electrode placement sites. These sites were the forehead and the thenar eminence (radial side of the palm of the hand) of the participants. Consistency of electrode placement during the individual tests was assisted by separate and coded electrodes provided by the manufacturer indicating which electrode was to be placed on the head and the distal region of the thenar eminence (see Figure 7.1, page 122). Once the electrodes were in place, these cables were connected to the OW sensor on an electrocardiogram (ECG) strap that was placed around the chest of each participant (see section 2.4). The test area was a team room that was isolated from the remainder of the facility which provided a quiet environment and was maintained at a constant ambient temperature. Prior to the commencement of the data gathering, trial runs were completed to estimate the duration of the test sequence and troubleshoot issues with the test environment. Trial runs were completed by the primary researchers (n =2) and members of the coaching staff (n =2).

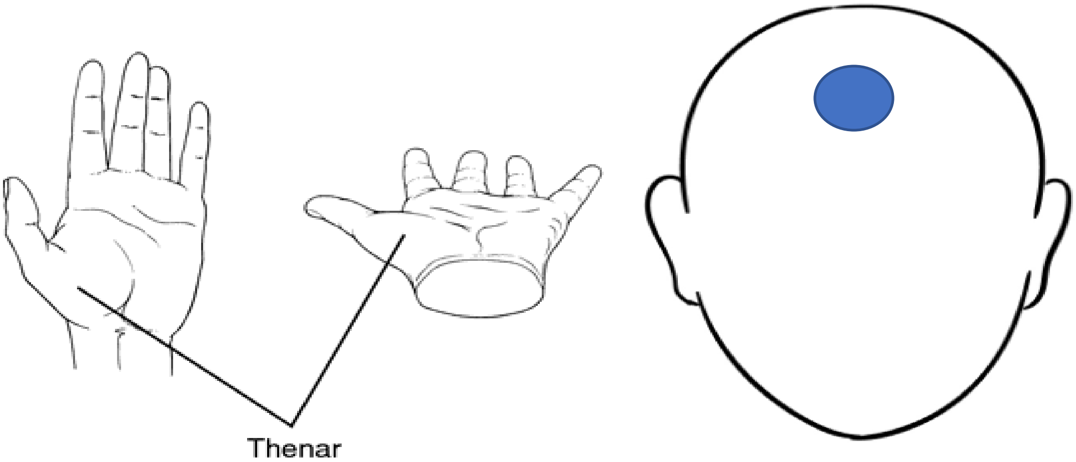


Figure 7.1 – (a) thenar eminence, (b) electrode placement location on the forehead

7.2.4 Data acquisition

During the individual player test days on Monday, Tuesday, and Thursday of each week, (data were collected over a 6-week period) each player was given consistent instructions per each iteration of the test. Each player was to arrive fasted and without caffeine or other stimulants and avoid stress prior to the test. Each data gathering session happened prior to squad training each morning which was generally between 7am and 8:30am. The ECG chest strap electrode pads were immersed in water the strap was attached around the torso of each player aligning the strap with the midaxillary line of the body. An electrode was placed on the middle of the players forehead, and another single-use electrode was placed on the base of the thenar region of the right hand of each player (Figure 7.1, page 122). The head and hand electrodes (via cables) from the sensor on the ECG strap was paired with an Apple iPad using Bluetooth.

Players were requested to lie in a supine position on a physiotherapy plinth and were advised to breath as normal. The players were requested to stay in a supine position until the measurement was completed; this was indicated by a notification sound from the data collection device (iPad). The tester then selected the 'save and analyse' option and the electrodes, along with the ECG strap was removed from each participant. Pearson's correlation coefficients were performed to assess associations between RSImod, DC potentials and POMS data.

7.3 Results

The initial values derived from DC potential reflect the basic level of activation for the individual being assessed. The amplitude of the signal after stabilises indicates the level of notional level of adaptability to stress and indicates the availability of energy reserves of the individual to perform activity (physical or cognitive).The data that were generated from the cohort were analysed using Excel (MS Corporation) to investigate possible correlations between the RSImod data, self-reported POMS data and the objective DC potentials data.

Individual player data were correlated over the test period comparing RSImod data, DC potentials data and self-reported POMS data. Weekly averages of RSImod, DC potentials data and POMS data were correlated. The research team concluded that the most appropriate data would be comparisons of three metrics (RSImod, DC potentials data and POMS data) over time and across all players that were tested during this case study.

DC potentials are based on brain energy that is derived from 1) Stabilisation point (level/grade) of DC potential (mV), 2). DC Stabilisation time (1.0-7.0) 3) Curve shape (1.0-7.0). For the purposes of the case series, the primary focus was on the values of the DC potential stabilisation point as the primary measure.

Table 7.1 All players' (n=11) summarised self-reported (POMS), DC potentials and reactive strength index modified (RSImod) data.

Player	Position B/F	Height (m)	Mass (kg)	POMS (± SD) Fatigue (1-10)	POMS (±SD) Sleep Quality (1-10)	POMS (±SD) Overall Stress (1-10)	IN/IL (Y/N)	Mean DC (±SD)Time (minutes)	Mean (±SD) DC Potential (1-7)	Mean (±SD) FC:CT	Mean (±SD) RSImod
1	B	1.87	98.4	1	7.50 (±0.83)	0.83 (±0.40)	N	2.12 (±0.47)	5.29 (±1.57)	0.80 (±0.02)	0.61 (±0.01)
2	B	1.84	90.1	1	8.85 (±0.37)	1.00	Y (IN)	2.28 (±0.49)	3.77 (±1.75)	0.80 (±0.02)	0.59 (±0.02)
3	B	1.83	87.3	2.35 (±0.63)	5.78 (±1.25)	2.42 (±0.51)	Y (IN)	2.10 (±1.29)	4.89 (±1.90)	0.81 (±0.03)	0.65 (±0.05)
4	F	1.78	102.4	1.66 (±0.52)	7.66 (±1.03	1.50 (±0.54)	Y (IN x 2)	2.12 (±0.50)	5.65 (±1.82)	0.82 (±0.04)	0.47 (±0.03)
5	B	1.7	74	2.14 (±0.69)	6.14 (±0.69)	3.57 (±0.53)	Y (ILX2))	1.75 (±0.70)	3.78 (±2.31)	0.74 (±0.07)	0.64 (±0.04)
6	F	1.83	117	1.75 (±0.50)	7.25 (±0.50)	1	Y(IN)	2.39 (±0.98)	5.28 (±1.96)	-	-
7	F	2.04	115.7	2.16 (±0.75)	5.16 (±1.47)	2.50 (±1.04)	Y (IN x 2)	2.64 (±1.15)	4.4 (±2.65)	0.83 (±0.03)	0.61 (±0.04)
8	F	1.83	117	2	7	1.50 (±0.54)	Y (IN x 2)	1.90 (±1)	2.87 (±1.94)	-	-
9	F	1.93	103	1.50 (±0.55)	6.50 (±2.58)	4.66 (±2.06)	Y(IN)	1.92 (±0.27)	3.90 (±2.35)	0.76 (±0.02)	0.59 (±0.02)
10	F	1.88	103.4	1.83 (±0.75)	5.33 (±1.21)	1.33 (±0.51)	N	1.79 (±0.70)	5.54 (±2.03)	0.74 (±0.04)	0.58 (±0.03)
11	B	1.88	97.6	1.60 (±0.54)	6.80 (±1.31)	1	Y(IN)	2.21 (±0.44)	5.59 (±1.31)	0.75 (±0.05)	0.55 (±0.02)

****Position B/F** (Playing position (back / forward), **IN/IL Y/N** (Recorded injury / illness Yes/No) **FC:CT** (flight time:contraction time)

The summarised data (see Table 7.1, page 124) identified a weak negative correlation (r = -0.17) between the RSImod data and the DC potentials (stabilisation point). A weak negative correlation was observed (r = - 0.02) between overall fatigue (POMS) and DC potentials (stabilisation point) along with a weak positive (r = 0.20) when correlating POMS and RSImod. Over the test period, DC potentials data generated greater standard deviation (±1.96) over the six-week timeframe when compared to the RSImod (±0.02) and POMS (±0.44).

7.3.1 Player overview

The DC potentials data reflect the time required for the stabilisation point to occur and indicates a transition from the active state to relaxed state. In this respect, the DC stabilisation point can be regarded as the general state of readiness of each player. The results from this cohort suggest there were great greater variance in DC potentials (neurological function) when compared to RSImod (neuromuscular function) or POMS (self-reported). The RSImod and POMs measures displayed a consistency in values across the participants over time. An example of this is Player 5 who recorded two bouts of illness. It is notable in relation to the consistency of the POMS data for fatigue, sleep quality and stress and the RSImod data which were recorded. The DC stabilisation point for Player 5 during the recorded test sessions displayed a greater variance over the same time period (see Table 7.1, page 124). Similar data were recorded for players 2, 3 and 11 with little variance in RSImod or POMS (overall fatigue sleep quality or stress measures). Player 9 recorded little variance in the RSImod over time. This player had similar values in sleep quality, stress, and DC stabilisation point (see Table 7.1, page 124).

Nine out of eleven players (81.8%) either reported an injury or illness or both injury and illness throughout the test period. Within these nine players, there were four players that reported either injury or illness on two occasions (Players 4, 5, 7 and 8). The injuries sustained by players 6 and 8 (lower limb) impeded these players from recording FC:CT and subsequently RSImod values. The POMS data for fatigue, sleep quality and stress for Player 6 (1.75±0.50, 7.25±0.50, 1±0 respectively) was not reflected in the DC stabilisation point data (5.28±1.96). Player 8 displayed a similar profile across the POMS data compared to the DC stabilisation point (see Table 7.1, page 124).

7.3.2 Case Study: Player 4

Player 4 was diagnosed with injuries on week 4 of the test period (lower limb) and week 5 (concussion) of the test period. Over the test period, the self-reported measures of POMS for three categories (i.e., fatigue, sleep quality and overall stress) displayed minimal variation with standard deviations of 0.52, 1.03 and 0.54 respectively. The test of neuromuscular function (i.e., flight time:contraction time, RSImod) were also consistent for the same time period with standard deviation values of 0.04 and

0.03 respectively. DC potentials values across the test period were more variable with reported standard deviations of 1.04 (DC potential overall readiness) and 1.82 (DC stabilisation point) during the same timeframe suggesting that the DC potentials may be more sensitive to fatigue than the other measures.

Observing the data during the week preceding the injury incidences (lower limb, week 3 and concussion in week five). The POMS Fatigue were an average score of three (low levels of self-reported fatigue), sleep quality were an average of six (self-reported high quality). Player 4 recorded an average DC Stabilisation Point of 6.76 and DC Stabilisation Time (minutes) were an average of 169 seconds (moderate readiness). During week three, they recorded an average RSImod of 0.49.

In week five, Player 4's self-reported POMS Fatigue were an average of 2.5, the POMS Sleep were self-reported as 6. DC Stabilisation Point averaged 6.1 and had an average DC Stabilisation Time of 2.12 minutes (moderate state of readiness). Player 4 did not record RSImod during week 5 due to the head injury (concussion) sustained.

7.4 Discussion

This case series in professional rugby union players attempted to evaluate the efficacy of objective DC potential measurements, neuromuscular fatigue data (RSImod) and self-reported data (POMS) as a comprehensive approach to monitoring player workload. DC potentials were the novel measurement approach in conjunction with external player load (RSImod) and self-reported POMS data. The DC potential metrics could provide coaches with parameters that suggest optimum states of readiness and when athletes have favourable adaptive capabilities (Heishman et al. 2018). In this study, the DC potentials data provided additional objective data that could be compared with the existing readiness protocols. The DC potentials data appeared to be more sensitive to changes in the players states of readiness over the six-week test period.

DC potential brainwave activity attempts to direct an athlete's readiness to perform, levels of internal stresses, cardiac measurements and offer a measurable insight into the neurological function of athletes. (Grainger et al. 2022). For the purposes of this study, longitudinal POMS data were gathered, however much of the POMS data were subjectively uniform suggesting that the POMS data would not provide a reliable marker for player monitoring purposes. In this case study, players tended to complete the POMS data as a matter of course without giving due diligence to the completion of the data. As many athletes in this study reported little deviation and recorded a very narrow range of values while with other players, there was a clear alteration in the POMS values that they self-reported. The management of players' readiness to train offers internal or external markers (subjective or objective markers). Subjective measures such as mood state, sleep disturbance or perceived levels of external stress are generally regarded as having a high degree of reliability with objective measures once suitably monitored (Saw et al. 2017). In this case study, the lack of variance across the cohort of players was notable, this may require additional scrutiny by coaching staff to ensure more accurate POMS values are reported. In this instance, it could be suggested that when POMS goes unmonitored, players gave little attention to inputting accurate values.

In dynamic high-performance environments such as professional rugby union franchises, it is important to individualise training load by using multiple tools to monitor individual workload responses (Hamlin et al. 2019). Where excessive fatigue goes unmonitored over protracted periods of time, this may lead exposure to injury risk including overreaching or overtraining which will impact on performance (Grandou et al. 2020). When fatigue levels are not accurately monitored and tracked, this could lead to a decrement in overall performance and injury risk (Tierney et al. 2018). When examining the values derived from the objective RSImod (CMJ - countermovement vertical jump) to determine the effect of workload and fatigue on neuromuscular performance. These data were highly consistent across most players for the duration of the test period. This was notable as many of the players (81.8%) recorded either an illness of an injury or both during the test period. In the majority of players' data, there was little variance observed in the RSImod scores over time.

The DC potentials data displayed variance for most players that was not evident by the POMS or RSImod data points. Selective multiple markers should be recorded and monitored, particularly markers that are objective and cannot be manipulated by player efforts or inputs. It appears that the data derived from this case study promotes the use of more that objective markers, such as DC potentials. Where high performance is the central focus, it could be argued that utilising DC potential measures may inform the more accepted and established self-report measures. In addition, the individual players' coefficient of variation (CV) could be used to assess if there is a reduction in the 'readiness to train' parameters. Where meaningful changes are detected and observed in individual players, the practitioner could alter the volume & intensity of workload.

7.4.1 Limitations and future research

As this was a case study, it is not clear whether we can categorically state that neurological function (DC potentials) could be used as a component in player monitoring. We can suggest that DC potentials are more sensitive to changes in professional rugby union players when compared to a neuromuscular measure such as RSImod or self-reported measures (POMS). A further limitation of the case study is the duration, all data was gathered over a six-week period. This length of time was not sufficient to establish long term patterns in the cohort of players. To identify the possibility that DC potentials are a viable objective measure, a longitudinal data would be required over the course of multiple competitive seasons.

For long term studies, a larger cohort of players would be required with the inclusion of a control group or alternative fatiguing protocol. A final limitation of the study was a full understanding of the proprietary algorithm and how calculations were derived by the product. In conclusion, this study supports the position that the most comprehensive means to monitor individual player workload is a multi-modality approach. This multimodal approach would involve the use of self-reported measures (POMS), a measure that can detect alterations in neuromuscular function (RSI or RSImod), in addition to other sources of objective data that may improve player welfare. This case series suggests that the inclusion of DC potentials would be an option as an additional objective measure as they have demonstrated promise regarding an increased sensitivity to indicating athlete readiness.

Post Publication Reflection

Regarding this pilot study chapter, many practices that originate in professional sports, can be marketed, and distributed to amateur athletes. This study attempted to investigate the usefulness of this technology (Omegawave) in a professional sporting environment. Consequently, it should have been stated clearly that this could be accepted as a relatively inexpensive system that could be used in community sport in testing readiness to train and participate. As mentioned during the viva process, the efficacy and sensitivity of the product lacked clarity due to the proprietary algorithms associated with the Omegawave product.

Suggested additional text to explain the physiological mechanisms for why the OmegaWave represents physiological/CNS readiness:

Omegawave summarises an athlete's current physiological state and provides key metrics focusing on the central nervous (CNS), cardiac and metabolic systems. The OW system takes a number of measurements relevant to an athlete's physiological condition. These measures include a) an ECG-based analysis, which provides heart rate variability (HRV) and cardiac/autonomic nervous system analysis and b) an EEG measure of 'DC-Potential' and CNS analysis, which indicates the brain's ability to regulate the CNS.

The OW system therefore provides a range of information pertaining to an athlete's current functional state, as well as a means to plot progressive physiological adaptations over time.

Removal/Editing of text:

The sentence **'**This case series suggests that the inclusion of DC potentials would be an option as an additional objective measure as they have demonstrated promise regarding an increased sensitivity to indicating athlete readiness.'

Should be edited to:

'This case series suggests that the inclusion of DC potentials would be an option as an additional objective measure to assess athlete readiness.'

Chapter 8 – Using Inertial Measurement Units to coach tackle technique proficiency in youth rugby players.

Preamble

Academic literature offers an abundance of research concerned with strength training, and the general preparation of adult players (professional and amateur) in relation to reducing injury risk. When we investigate injury reduction techniques or guidance directly related to younger rugby players (<18 years old), there are gaps in the literature. This is particularly evident when coaches seek practical tools to make the game of rugby union safer. It has been noted previously that improving tackle technique in younger players may reduce head injury incidence such as lacerations and concussion. This proof-of-concept study examined to what extent a smart-phone based inertial measurement unit can be used as an educational tool for players and coaches alike when practicing rugby tackles. This proof-of-concept utilised IMUs and a novel mobile application which was developed specifically for this study. It is well established in the literature that many concussions and associated maxillofacial injuries that occur in rugby occur in the tackle area of the game. In the modern game of rugby union, the emphasis is to have a double tackle on opposition players. This emphasis requires players to tackle opposition players in the upper extremity (i.e., to tackle the area where the rugby ball is held) and in the lower extremity (i.e., around the knees and or shins of the opposition players). This is generally the coaching direction given to adult playing populations. In the age grade (<12 years old) and youth grades (>12 – 18 years old), many coaches attempt to coach players to tackle at a zero-tackle angle, keeping their heads to the outside and attempt to complete a tackle on an opposition player on the quadriceps area of the opposition players. The rationale for this coaching practice is that this may enable players to execute safer tackle technique and reduce accidental head contacts with the opposition player. By practicing more technically correct tackle technique, this may reduce the incidence of injury risk exposure for the tackler and person being tackled.

Publication citation:

Daly E, Esser P, Griffin A, Costello D, Servis J, Gallagher D, Ryan L. Development of a Novel Coaching Platform to Improve Tackle Technique in Youth Rugby Players: A Proof of Concept. *Sensors. 2022 Apr 26;22(9):3315*. https://doi.org/10.3390/s22093315

8.1 Introduction

Rugby union is a field sport that is played at amateur and professional levels by male and female players globally. The most recent data from World Rugby report that the number of registered players stands at approximately 9.6 million across 123 countries (World Rugby Participation Data). One of the most prevalent injury risks associated with the sport involves tackle collisions with opposition players. Injury data from rugby surveillance projects in Ireland involving amateur rugby players (Irish Rugby Injury Surveillance (IRIS), 2018–2019) cited that the most common injuries occur in the physical contact areas (i.e., tackling, rucks) of the game. In this report, it was recorded that tackling an opponent accounted for the majority of match and training injuries in amateur rugby (59% of the overall injury burden). IRIS also found that the most frequently reported match injury for both male and female players was concussion (11% and 19%, respectively). In the United Kingdom, injuries to the head, face and shoulder were the most common injury sites in amateur youth rugby playing populations, with over 50% of the injuries occurring in the tackle or collision areas of the game (Archbold et al. 2017). Data provided by research in school-level rugby union in Australia, with a similar age profile (age 13 ± 4.5 y), suggested that injuries to the head and face accounted for 33.7% (n = 112) of all injuries (Leung et al. 2017). From the overall total of 332 injuries, there were 61 cases of suspected concussion injuries. Additional research found that amateur players who had an incorrect head position relative to the ball carrier resulted in a higher incidence of concussions, neck injuries and facial fractures when compared with players that performed tackles with the correct head position (the injury incidence with incorrect head positioning was 69.4/1000 tackles, compared with the injury incidence with correct head positioning of 2.7/1000 tackles) (Sobue et al. 2018).

When compared with professional rugby, the injury incidence involving tackling in adult amateur rugby was lower than that in the professional game but had a higher incidence rate when compared with youth rugby (Yeomans et al. 2018). This suggests that future injury reduction strategies must be aimed towards the tackle area in the game of amateur rugby union (Yeomans et al. 2018). In youth rugby, a suboptimal tackle technique may contribute to an increased injury risk, but this risk can be reduced by implementing safer techniques during training sessions (Burger et al. 2017). At youth rugby levels, it has been reported that many coaches have relied on informal or anecdotal resources (e.g., previous playing experience or observation of matches) to develop their knowledge of tackle training (Hendricks et al. 2018).

One proposed mitigation strategy to reduce tackle-related injuries in youth populations may be to enhance coaching skills that increase tackle proficiency and technical capacity in youth rugby players (Hendricks et al 2017, Hendricks et al. 2018). Additional research supports current rugby coaching practice, whereby a player should have their head positioned upwards and be facing the ball carrier to improve tackle technique proficiency (Hendricks et al. 2014). This training technique results in a ‘head up’ position which allows the tackler to perform a shoulder tackle on the mid torso of the opposing player. This suggested tackle technique can assist the head placement of the tackler once the initial contact is instigated and can result in a more proficient tackle technique (Hendricks et al. 2014).

Evidence suggests that tackle mechanism-related research may act as a mitigating factor in reducing tackle-related injuries (Burger et al. 2020). Further research has proposed that the tackler trunk had a direct effect on head kinematics when utilising tackles aimed at the mid and/or lower trunk of the player being tackled (Tierney et al. 2018). With respect to youth rugby, it has been advised that the ‘head up and forward before contact’ coaching cue may result in safer contact techniques (Hendricks et al. 2016). This study found that players who were deemed to be concussed displayed a ‘down’ or ‘away’ head position on contact which may lead to an in-creased risk of head or neck injuries (Hendricks et al. 2016). This coaching instruction is a technique that could be incorporated by coaches to instruct players to maintain the ‘up and forward’ head position into tackle contact and not only in anticipation of contact with an op-posing player. Injury risk may be reduced when coaches are able to observe and measure tackle proficiency by quantifying the quality of the tackle technique.

For example, research has demonstrated the use of observable technical criteria which outline a list of clear distinct phases of tackling (i.e., pre-contact, contact and post-contact). This study analysed the tackle technique of each player which was scored one point or zero depending on the action performed during pre-contact, contact and post-contact (Davidow et al. 2018). For example, during the pre-contact phase, if the tackler was in a ‘head up and forward’ angle of approach, this was deemed as a good action and awarded one point. The sum of the points allocated was used to determine the technical proficiency score of the player during tackling or contact events. Further research has found that tacklers that had an incorrect head position or that had intentionally used a poor technique tended to result in more injuries as the players’ head and neck were in an incorrect position (Sobue et al. 2018).

By extension, these safer tackle techniques (i.e., ‘head up and forward’ and zero angle of approach) could be applied to other contact areas (e.g., rucks, scrums) to mitigate against injury in contact areas of the game. In amateur youth rugby, coaches that deliver tackle training may have knowledge gaps specifically related to their own competencies in coaching an effective tackle technique (Hendricks et al. 2017). If coaches were to implement a diagnostic prescriptive model to address areas of improvement and monitor ‘ideal’ movement in all contact areas, this may reduce injury risk as coaches could instruct the optimal movement technique during contact training (Hollander et al. 2021). By utilising contemporary wearable technologies such as inertial measurement units (IMUs), the movement of players can be captured. The use of IMUs is well established in the literature (Ghattas et al. 2021). There is support for the use of IMUs as tracking devices for human movement in sport and translating specific movement actions which can be detected and extracted using IMUs (Cust et al. 2019). A recent study suggested that the use of microprocessor technology (such as that contained in IMUs) is a valid method to detect human motion in contact events in rugby union (Chambers et al. 2019). At present, IMUs are not linked to visualisation platforms for coaching tackle technique.

The present study aimed to demonstrate a proof of concept for a novel tackle technique training platform using IMUs and a bespoke mobile application developed for a mobile device (e.g., a mobile phone or tablet). It was hypothesised that developing a mobile coaching platform which utilises live IMU data could potentially lead to improved coaching strategies for amateur and novice coaches regarding tackle technique. This coaching platform could, in turn, reduce the incidence of upper head, neck and facial injuries in youth rugby by better informed coaching practice. The platform could therefore potentially constitute part of an injury reduction strategy for amateur or novice coaches that are responsible for instructing safe tackle practice in youth rugby playing populations.

8.2 Materials and Methods

A novel prototype mobile application was developed by the research team for use on mobile phones. The prototype application was initially developed for laptop usage and further engineered for use on a mobile phone. The development of this mobile functionality (e.g., mobile phone/tablet) was explicitly for use in an applied setting by amateur coaches for training sessions with amateur youth rugby union players.

8.3.1 Technical Description

Technical Description—Inertial Measurement Units (IMUs)

The *Shimmer3 Wireless Sensor Unit* (Shimmer Research Ltd., Dublin, Ireland) is a wearable device that contains two accelerometers, a gyroscope, and a magnetometer. This combination of sensors is an IMU with nine degrees of freedom (DFs). The proposal would use the IMUs to capture the orientation of a player’s body in a tackle simulation training exercise by using kinematic data which notionally focused on the orientation of a player’s upper body (i.e., scapulae and shoulders).

Technical Description—Development of the Prototype Mobile Application

This bespoke mobile application is a lightweight application connecting the IMU data streams directly to a 3D model in the prototype mobile application. The axial output from the IMU is converted to Euler angles that are applied to the model in real time within the mobile application. Initially developed for a laptop using the Unity 3D Game Engine, it was further engineered and ported to a mobile device to increase access to data during training sessions. Unity3D was used in the development of the Android application as it has an integrated physics engine which was used when manipulating the nine DFs provided by the IMU. Converting from Euler angles to quaternions was necessary to manipulate the data returned from the IMU.

The system is composed of three core applications and a database (see Figure 8.1, page 134). There are two cross-platform applications and a representational state transfer application programming interface (REST API) server application backed by the database instance. The applications may be deployed on Android or Windows 10 (Microsoft Corporation, Redmond, WA, USA) devices, and the server application was deployed to Azure Web Services (Microsoft Corporation, USA) for this project.

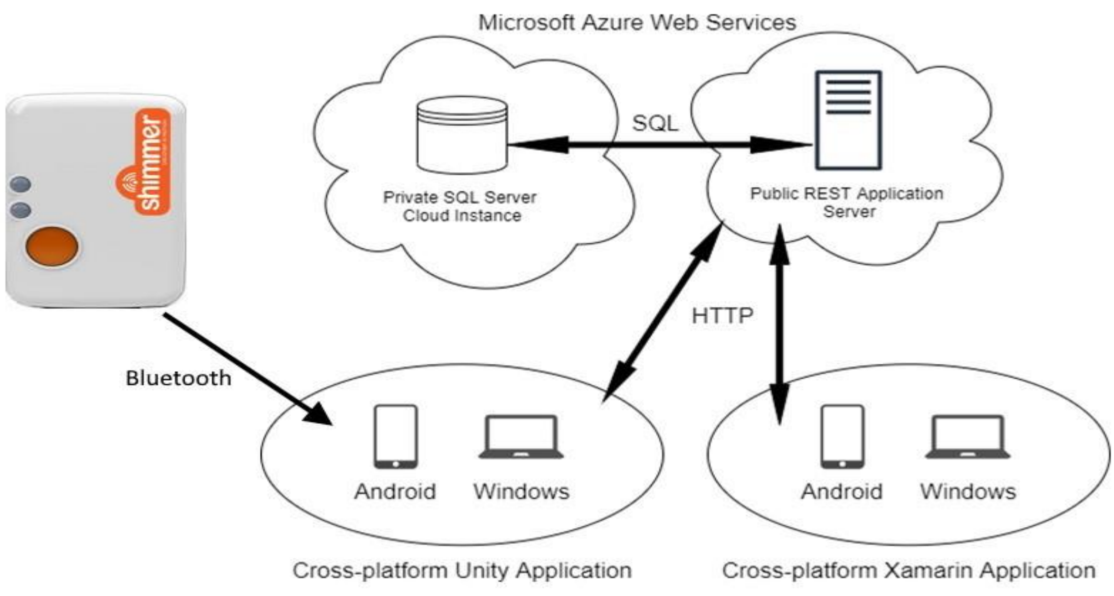


Figure 8.1 . Program architecture and data flow

8.3.2 Ethics

Ethics for this study was granted by the Taught Programme Research Ethics Committee (TPREC) in Galway Mayo Institute of Technology (GMIT_TPREC_250120). All participants provided written and/or verbal informed consent prior to data collection.

8.3.3 Data collection

Four male participants (age 18.1 ± 0.6 y/height 179.5 ± 3.3 cm) were fitted with a GPS vest (VX Sport Systems), and the IMUs were inserted into the GPS pocket located be-tween the scapulae of the GPS vest. This enabled a constant position on the participant to measure the roll, pitch, and yaw (i.e., rotation around the XYZ axes). The participants calibrated the IMUs by assuming a standing position and completing rotational, hinge and gait movement patterns.

Prior to the tackle simulation tests, all participants undertook a warmup that included technical instruction (the participants were not rugby players), a physical mobilisation and a familiarisation with each test condition. The participants were instructed to approach a foam-padded surface which simulated the contact area during tackle events to become familiarised with the test area. Once the GPS vests and IMUs were worn by the participants, they were instructed to approach the padded surface with their hips hinged and their heads positioned upward parallel to the ground plane. When the participants touched the padded area with their shoulder, tape (zinc oxide) was applied to the padded area to measure where their shoulder met the padded area; this indicated each participant's zero angle of approach to the foam-padded surface when testing commenced.

Each participant engaged in ten static simulated tackle events (five attempts on the left shoulder and five attempts on the right shoulder). These static tackle simulations were executed in a parallel direction (i.e., simulating a zero angle of approach to the ground plane of the test area). The simulated tackles that were performed in this manner produced a green light on the prototype mobile application which indicated a safe tackle (see Figure 8.5, page 139). The participants simulated ten tackle events that were approximately ten degrees above and ten degrees below these parallel tolerances, and these (unsafe tackles) were indicated by a red light on the mobile display unit (see Figure 8.5, page 139). The parameters of ten degrees above and below the zero angle of approach were measured and marked on the foam-padded surface using an inclinometer mobile application (Clinometer, France).

8.2.1 Results

The test battery provided a proof of concept for the primary objective of modelling the motion of a participant in a tackle event using an IMU and a novel prototype mobile application. The prototype application modelled the IMU unit in a 3D space and demonstrated the orientation during a tackle event to the researchers. These tackle event simulations provided a real-time stream of data that displayed the angle of tackle for the researchers to observe on the mobile phone device. The data collected were saved and used to replay the tackle technique to each participant which assisted the re-searchers in modifying and coaching the participants' tackle posture characteristics. The data returned were used to calculate the roll, pitch, and yaw of the IMU on the participant and update the 3D model on the mobile phone device. The pitch, roll and yaw are the rotations about the X, Y and Z axes, respectively. These axes are shown in Figure 8.2 (page 136) for the IMU which are aligned on the participant with the Y axis along the spine and the X axis across the shoulders.

Table 8.1 (page 137)shows a sample of the data returned from the IMU during the testing phase of the project. Four readings are provided with 38 data points for each. The IMUs return data from the accelerometers, the gyroscope, and the magnetometer. These data are used by the processor within the IMU to produce the axis angles and the quaternion values. For the purposes of this project, the data from the low-noise accelerometer. gyroscope, magnetometer, axis angle and quaternion were saved and imported for use in displaying the orientation of the Unity 3D model. Each data point is timestamped, and this is used to order the data points during a replay of a tackle event. Based on these data, the axis angle and the quaternion values are calculated by the IMU processor during the data streaming process. These values are filtered for use by the Unity application and stored in a JavaScript Object Notation (JSON) format for ease of processing within the application. These data are illustrated in Figure 8.3 (page 138) for a single reading.

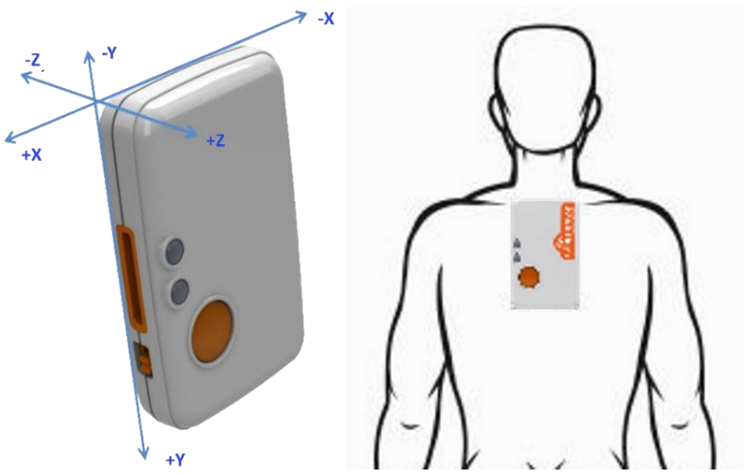


Figure 8.2: Shimmer axes of rotation demonstrating indicative placement of the IMU.

Table 8.1 . Sample reading of data returned from the inertial measurement unit (IMU). Accelerometer values are in metres per second squared (m/s2), the gyroscope returns degrees per second (°/s) and the magnetometer provides flux (cgs) values.

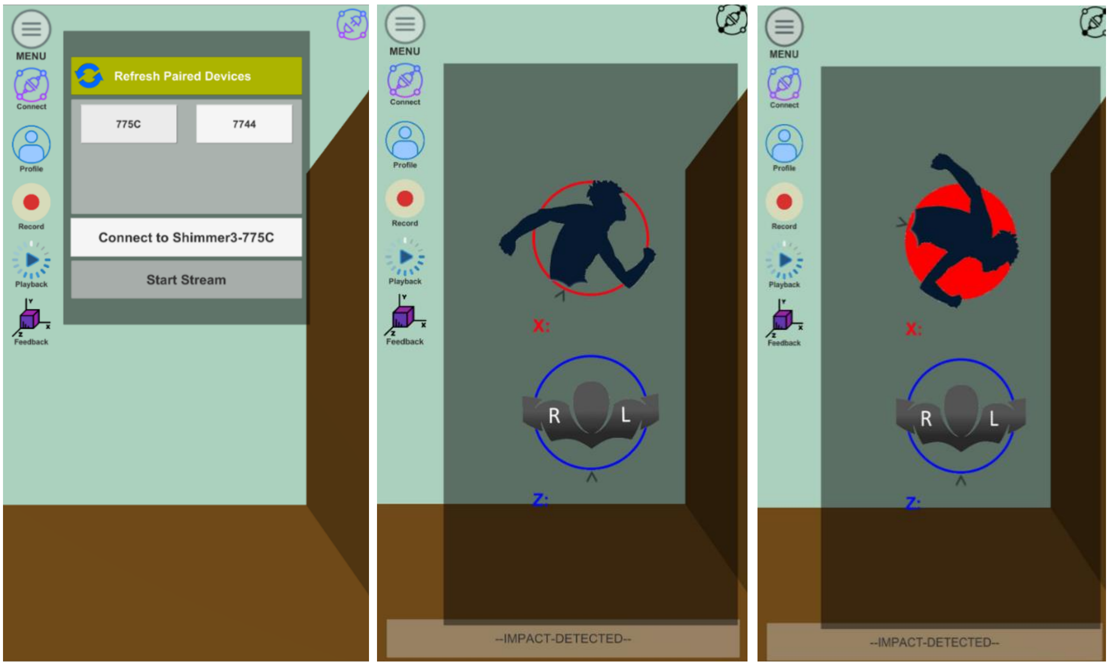
	Reading 1	Reading 2	Reading 3	Reading 4
Timestamp_RAW	11461017.00	11467417.00	11473817.00	11480217.00
Timestamp_CAL	189443.36	189638.67	189833.98	190029.30
Low_Noise_Accelerometer_X_RAW	2006.00	2006.00	2007.00	2006.00
Low_Noise_Accelerometer_X_CAL	2.05	2.08	2.05	2.07
Low_Noise_Accelerometer_Y_RAW	2064.00	2062.00	2064.00	2063.00
Low_Noise_Accelerometer_Y_CAL	2.68	2.68	2.67	2.68
Low_Noise_Accelerometer_Z_RAW	1219.00	1218.00	1220.00	1221.00
Low_Noise_Accelerometer_Z_CAL	11.24	11.25	11.23	11.22
Wide_Range_Accelerometer_X_RAW	16.00	52.00	48.00	36.00
Wide_Range_Accelerometer_X_CAL	-0.63	-0.63	-0.65	-0.57
Wide_Range_Accelerometer_Y_RAW	-1060.00	-1056.00	-1088.00	-960.00
Wide_Range_Accelerometer_Y_CAL	-0.01	-0.03	-0.03	-0.02
Wide_Range_Accelerometer_Z_RAW	-17352.00	-17336.00	-17352.00	-17316.00
Wide_Range_Accelerometer_Z_CAL	10.38	10.37	10.38	10.36
Gyroscope_X_RAW	-24.00	-14.00	-20.00	-9.00
Gyroscope_X_CAL	-0.66	-1.19	-1.08	-0.81
Gyroscope_Y_RAW	43.00	78.00	71.00	53.00
Gyroscope_Y_CAL	0.37	0.21	0.31	0.14
Gyroscope_Z_RAW	-11.00	-8.00	-4.00	3.00
Gyroscope_Z_CAL	0.17	0.12	0.06	-0.05
Magnetometer_X_RAW	1023.00	1791.00	-2.00	1535.00
Magnetometer_X_CAL	14.58	20.73	13.82	17.27
Magnetometer_Y_RAW	9728.00	13824.00	9216.00	11520.00
Magnetometer_Y_CAL	-1.53	-2.69	0.00	-2.30
Magnetometer_Z_RAW	23297.00	21761.00	19457.00	22273.00
Magnetometer_Z_CAL	-34.93	-32.63	-29.17	-33.39
Pressure_RAW	20384.00	20385.00	20385.00	20384.00
Pressure_CAL	10514.43	10515.09	10515.09	10514.43
Temperature_RAW	32862.00	32862.00	32862.00	32862.00
Temperature_CAL	8.06	8.06	8.06	8.06
Axis_Angle_A_CAL	0.07	0.07	0.09	0.08
Axis_Angle_X_CAL	-0.14	-0.04	-0.02	0.14
Axis_Angle_Y_CAL	0.83	0.81	0.72	0.76
Axis_Angle_Z_CAL	-0.54	-0.58	-0.70	-0.63
Quaternion_0_CAL	1.00	1.00	1.00	1.00
Quaternion_1_CAL	0.00	0.00	0.00	0.01
Quaternion_2_CAL	0.03	0.03	0.03	0.03
Quaternion_3_CAL	-0.02	-0.02	-0.03	-0.02

"T"   : 189443.36,   // Timestamp
"LN_X":   2.05,   // Low Noise Accelerometer CAL Values
"LN_Y":   2.68,
"LN_Z":   11.24,
"G_X" :   -0.66,   // Gyroscope CAL Values
"G_Y" :   0.37,
"G_Z" :   0.17,
"M_X" :   14.58,   // Magnetometer CAL Values
"M_Y" :   -1.53,
"M_Z" :   -34.93,
"A_A" :   0.07,   // Axis Angle Calculated Values
"A_X" :   -0.14,
"A_Y" :   0.83,
"A_Z" :   -0.54,
"Q_0" :   0.99,   // Quaternion Calculated Values
"Q_1" :   -0.01,
"Q_2" :   0.03,
"Q_3" :   -0.02

Figure 8.3 JavaScript Object Notation (JSON) formatted data for a single reading.

```
void quaternianToEuler(double q0, double q1, double q2, double q3)
{
    this.roll = Math.atan2(2.0D * (q0 * q1 + q2 * q3), 1.0D - 2.0D *
                           (Math.pow(q1, 2.0D) + Math.pow(q2, 2.0D))) *
                           180.0D / 3.141592653589793D;
    this.pitch = Math.asin(2.0D * (q0 * q2 - q3 * q1)) *
                           180.0D / 3.141592653589793D;
    this.yaw = Math.atan2(2.0D * (q0 * q3 + q1 * q2), 1.0D - 2.0D *
                           (Math.pow(q2, 2.0D) + Math.pow(q3, 2.0D))) *
                           180.0D / 3.141592653589793D;
}
```

Figure 8.4 Code sample for calculating roll, pitch, and yaw.



(a) *(b)* *(c)*

Figure 8.5: (a) Mobile application connecting to the inertial measurement unit (IMU), (b) calibrating IMU to the participant and (c) modelling an unsafe tackle indicated by the 'red light' display.

The quaternions are used to calculate the roll, pitch, and yaw to be reflected in the Unity 3D model. The calculations for these are conducted with the method shown in the code sample in Figure 8.4 (page 138) and are based on standard math formulas for this purpose. Once these values are calculated, the 3D Unity application updates the orientation of the model and demonstrates the modelling of a player's motion, using the IMU in a tackle event in Figure 8. Tackle angles that were deemed safe (i.e., within ten degrees of a zero angle of approach) displayed a 'green' light on the mobile display, and tackles that were deemed unsafe displayed a 'red' light (i.e., outside the safety parameters of ten degrees above or below the zero angle of approach) on the mobile phone display (see Figure 8.5, page139).

8.3 Discussion

The objective of this study was to demonstrate a proof of concept for a novel tackle technique training platform using IMUs and a bespoke mobile application developed for a mobile device (e.g., a mobile phone or tablet). This novel mobile coaching platform could be used to capture the motion and orientation of a participant's body during tackle events in rugby. The prototype coaching platform utilised a novel mobile phone application and IMUs as a sensor-based recording system. This study successfully provided a proof of concept for the coaching platform to demonstrate safe or unsafe angles of approach during tackle events in tackle technique training for amateur coaches. Participants demonstrated tackle angles that provided kinematic data of the upper body in static simulated tackle technique training. As this is a prototype tackle technique coaching platform, further development remains to refine the visual warning system for amateur coaches. The current prototype mobile phone application can provide visual feedback to the coach using a traffic light system (green or red) based on the angles of rotation around the XYZ axes. In this study, suggested tolerance parameters (i.e., ±10° the zero angle of approach) of the tackle were based on existing kinematic rugby tackle data (Tierney et al. 2018, Hollander et al. 2021). The system displays a green or red indicator light along the axes depending on the set tolerance parameters utilised in the study. The model on the mobile user interface (UI) changes colour as the angle of rotation approaches the tolerance parameters (ten degrees above or ten degrees below the parallel plane) which indicates either safe (green) or unsafe (red) angles of approach in a tackle event. The suggested parameters (±10°) were primarily selected as a guide to novice coaches and assist in a 'head up and forward' approach to tackle safety. By adopting this approach to coaching safer tackle technique, it may assist in improving tackle posture and enable novice youth players to target the upper legs and lower trunk area of the ball carrier in live tackle scenarios.

As previously mentioned, coaching appropriate safer tackle technique may reduce injury risk in youth players or in adult amateur players (den Hollander et al. 2019). The data provided by this platform could constitute part of an injury reduction strategy for amateur or novice coaches. Recent research has suggested that when coaches emphasise a proficient tackle technique in training, it has a positive relationship with the perception of importance for players in tackle training and overall injury reduction (Hendricks et al. 2020). The data provided by this novel coaching platform could improve the knowledge of tackle technique and the development of better implementation techniques for the coach. Where coaches are capable of instructing, guiding, and offering feedback to players on tackle technique, the players' tackle proficiency and self-efficacy progress in conjunction with better technique (Hendricks et al. 2020).

A future development of this platform for amateur coaches would be to validate the novel coaching platform against video analysis of tackle technique as video analysis is a recognised method for analysing biomechanical motion in rugby training or during active competition (Hendricks et al 2020). Evidence suggests that combining video analysis and wearable technology such as IMUs is a more robust method to investigate human motion in a sports setting (Adesida et al. 2019, Schlipsing et al. 2017, Tyson et al. 2018, Yeoman et al. 2020). This application of using video analysis for tackle technique may alter lower extremity kinematics for inexperienced youth rugby players which could reduce head accelerations during tackle events (Kung et al. 2020). One advantage of using video analysis in sport is the ability to infinitely pause, replay and focus on specific segments of training or competitive conditions. This capability to pause and replay could aid amateur coaches in identifying tackle technique deficits, with a greater awareness of injury risk in rugby settings (Gardner et al. 2015).

The present study offers a potentially novel platform to assist amateur coaches in identifying injury risk and improve the safety of tackle technique for youth rugby union players without the use of additional video analysis. The novel platform developed for this study has the capability of instant feedback or review of individual tackle technique during a training session. The platform has the added functionality to store and review tackle training sessions for a number of players which could be reviewed by the player and coach at a later date. The use of this novel coaching platform could facilitate vision training for tackle performance and may assist in developing the anticipation skills required for tackling and contact skills in rugby union. Vision training has been demonstrated to be a proposed concussion reduction strategy as it may assist in im-proving the ability to 'scan' the visual field for opponents and anticipate physical impacts (Kung et al. 2020). The use of mobile applications and technology for sports coaching is well established. Technology and mobile applications can provide the means of gathering and analysing data which can then be translated into coaching practice for amateur coaches.

8.3.1 Limitations

There are limitations to the current research, even though it has demonstrated that data gathered from wearable sensors (IMUs) can increase the potential to correct tackle technique using a mobile coaching application. The focus of this initial stage of research was to demonstrate that IMUs and a mobile application could model an optimum safe tackle technique in training exercises by suggesting an optimum approach to the development of a safe tackle technique. In turn, this type of technology could assist a novice coach in developing a safer tackle posture for tacklers (i.e., 'head up and forward' posture). The current research could be further enhanced to identify specific causes of injury that occur with a poor tackle posture during tackle events in training and ultimately in live match play. As the game of rugby is a dynamic field-based sport, it is challenging to predict how tackles will be executed in real time. Consequently, the modelling in this proof of concept is constrained by limitations in the existing mobile application to adjust for non-optimum tackle angles. In many live tackle situations, the tackler may be unable to execute the optimum tackle angle. During these instances, the tackler may not be able to target the upper legs or lower trunk area of the ball carrier. This may mean that a tackler executes a tackle below the knees or above the waistline of the ball carrier. In these scenarios, these tackle angles would be outside the current parameters of ±10° and deemed unsafe using the current mobile application. Future iterations of the mobile application may need a facility where the optimum tackle angle could be adjusted, as this may replicate a more 'real' reflection of tackling in live matches.

A further limitation of the current research is in respect to the ±10° on tackle approach. The current research selected ±10° based on existing kinematic rugby tackle data which suggested a safe tackle approach would target the upper leg and lower trunk. Using an initial zero angle of approach to the tackle and allowing ±10° tolerance would mimic a would-be tacklers angle of approach to an oncoming ball carrier. The rationale for using ±10° as an angle of approach as that it may assist in the 'head up and forward' motion for players to recall, and novice coaches to cue in coaching tackle safety. Equally, it could be suggested that ±15° or other angle variations could be used as a safe tolerance; however, this was beyond the scope of the current paper. Using different tolerances (e.g., ±5°, ±15°, ±20°) may yield different results and assist in furthering the development of the current mobile application.

Future research development of this proof of concept will be to compare the current platform with video analysis as a means of reliability and validity testing. The current study demonstrated that it is possible to model static tackling posture characteristics in novice rugby players. The second phase will involve modelling live tackling events that measure proficient angles of approach to tackle technique and measurement of the forces during tackle impacts. This development will assist in the overall quality of coaching for tackle technique training in amateur rugby players and amateur coaches.

A final limitation of the present study was that all participants were male, which meant that the research team was unable to conclude if this prototype coaching platform may be suitable for female rugby players. This should be a notable consideration due to the differences in body mass and muscular distribution between male and female players in the amateur game of rugby union. This may lead to the development of alternate means of tackle technique coaching platforms and tackle proficiency strategies for females due to these parameters.

8.3.2 Conclusions

The objective of this study was to demonstrate a proof of concept for a novel tackle technique training platform using IMUs and a bespoke mobile application to capture the orientation of a youth rugby player's body during a tackle event. This study successfully demonstrated the development of a novel cross-platform software application for use in combination with IMUs. Wearable technology combined with the development of be-spoke mobile applications has the potential to capture motion and potentially improve tackle technique proficiency to reduce injury risk in youth rugby. With advances in wearable technology, and associated reductions in cost, the development of novel mobile applications for improving tackle technique will enhance the potential for such applications to be widely utilised in amateur and community sport settings. In addition, this use of wearable technology and the developed bespoke mobile application could be utilised to monitor improper body position during activities of daily living, i.e., sitting posture or examining different physical strengths (asymmetries) of the left or right part of the body due to physiological or anatomical changes.

Chapter 9 - General Conclusion

9.1 – Summary of Findings

Concussion is a common injury in contact and collision sport which occurs at both amateur and professional levels. The injury, and associated complex long-term issues, such as persistent post-concussion symptoms, can be identified in athletes regardless of gender, age, or level of sport. In most sports settings, the largest concern is the accurate and timely identification of the injury. When concussion occurs, it is crucial that those involved attempt to instigate appropriate procedures to recognise, manage and treat the individual who has been injured. Frequently in amateur sport, concussion goes undiagnosed or is not truly recognised as an injury when compared to more obvious musculoskeletal injuries such as ruptured ligaments or bone fractures. A challenge exists to continually reiterate that concussion is a brain injury which should not be trivialized or lightly dismissed. In this regard, one of the primary considerations for the current research was to ascertain the current background in concussion identification and management.

As discussed in chapter two, many professional sports organisations have extensive medical teams available for the treatment of injury with their athletes. Generally, this means that athletes have comprehensive medical care available to them and accepted recovery and return-to-play procedures in place to protect the athlete from further injury. In amateur sports settings, any form of medical team support (i.e., physiotherapists, medical doctors) can oftentimes be unavailable. Adding to these underlying circumstances, can be the additional challenge of accurate identification and diagnosis of concussion. In amateur sports, it may be difficult to identify concussion due to the broad array of symptoms. In many amateur sports, there may be little or no medical support to assist in the identification of symptoms due to a lack of suitable resources or personnel. The fundamentals of concussion management are early identification, removal from the activity, and establishing an appropriate treatment pathway for the injured athlete. The systematic literature review in chapter two examined the current pitch side identification protocols for athletes in amateur or professional sport.

The review (chapter 2) highlighted that most studies on pitch side management of concussion were drawn from professional or elite environments which had comprehensive medical support. In addition, the level of research associated with females was severely unrepresented with most of the participants being male. One aspect that was noteworthy were the variety of concussion assessment protocols detailed in the studies. In this regard, a consensus was that concussion identification and assessment needs to be multimodal due to the variance in symptomology, and duration of recovery from the injury. A major finding from this review was the shortfall in research for amateur athletes in community settings. In amateur sports, the responsibility for identifying potential concussions frequently rests with team coaches, parents, or match officials. Understandably these circumstances are exacerbated as many coaches, parents and officials do not have the necessary knowledge and/or competence to assess a complex neurological issue such as concussion. As a consequence., these factors mean that there is a lack of visibility of accurate concussion incidence rates in amateur sport, which may expose amateur athletes to further injury or in some instances, long term neurodegenerative disorders due to an absence of appropriate protocols.

Chapter three addressed a strength training method that has been anecdotal and widely discussed and/or postulated as a means of reducing concussion incidence across amateur and professional sport. Many strength coaches have suggested that developing neck strength can be a utilized as possible means to reduce head injury. The premise of this anecdotal theory is that by developing neck musculature to become more rigid, it may be capable of withstanding high impact forces in sports such as boxing or collision sports such as rugby union. These arguments have centered on increasing neck girth and therefore increasing overall neck muscle strength. The findings from the systematic review in chapter three had all male participants and were limited in the sports discussed (i.e., rugby union and American Football). Although two studies did report an improvement in overall isometric neck strength, they did not discuss how these findings would translate to game play situations or if they would reduce cervical spine injuries. Even though neck strength is frequently discussed as a mitigating factor for reducing concussion incidence, there is currently a lack of evidence to support the claims due to absence of longitudinal data in either professional or amateur sports.

To understand concussion from an athlete standpoint, this thesis incorporated a mixed methods approach. As mentioned, the voice of the athlete was required to gain insights from a qualitative research perspective. Chapter four sought to understand the perception of injury risk in rugby union, and how players dismissed the short term and long-term implications of multiple concussions over the course of their playing careers. What became apparent from these interviews were the incessant pressures that players put themselves under on a continual basis. These internal and external pressures manifested as peer pressure from their fellow professional players and more directly from coaches associated with the clubs. The distressing aspect of these types of influences were that players normalised concussion and other physical injuries. Head injuries were trivialized and discussed as minor inconveniences or not serious injuries. In many cases, the players did not disclose their concussions or were expected to play while concussed.

The interviews highlighted one of the most challenging aspects of being a professional rugby player which is the fear of failure. It became evident that failure for these players was present in many forms. While they were injured or were unable to play, the fears associated with isolation from their peer group were debilitating. Their greatest fears were long term injury which could result in losing their playing contracts, and subsequently, their livelihoods. In some instances, failure in themselves manifested because of cognitive decline and parallel failures in their mental health or personal lives. Chapter five further examined the mindset of rugby union players. Many of the players viewed themselves as ‘commodities’ and were expected to play while hurt. These alpha male viewpoints generated major components of their personal identities. These ideals added an elevated status whereby they were willing to play while being concussed or covering up concussions in a display of manliness. It is generally accepted that many practices which exist in professional rugby union, filter through to the amateur levels of the sport. In this regard, how concussions are disclosed and managed may influence all levels of the game and assist in player and coach education across all strata of rugby union.

Chapter six explored the concept of objective concussion management and how objectivity could enable improved player welfare. The themes revealed in this research highlighted the importance of impartial medical assistance, and where any doubt existed, players should be removed from play whether they are professional or amateur. An interesting finding underlined the need for decisions to be made independently of the injured players. This meant that players wanted the decisions made by medical staff without interference from coaches or the player’s own opinion. In addition to this point, most players reiterated the need for more robust return-to-play protocols to assist the long-term health of players in retirement and future generations of rugby players. The use of protective equipment such as mouthguards and soft-shell head protectors were discussed in the context of both professional and amateur players. The comments from this cohort of retired players suggest that protective equipment is not useful in mitigating against the effects of persistent long-term impacts while playing rugby.

The third theme investigated in this thesis was focused on practical measures that may assist in mitigating against concussion injury risk in rugby union. This theme was researched by studying the effects of fatigue on injury risk exposure incidence in professional rugby players. Chapter seven discussed the role of fatigue and how objective measures such as biopotentials could be used as a predictive tool which may highlight players who were at risk of injury. There are a multitude of applications and metrics used to monitor player workload in professional and amateur players. Most of these tools are based on monitoring workload and managing the total workload of players over given time periods. The reason behind these efforts to manage workload lies in established training principles. These training principles suggest that players who are overreaching or overtrained may be at a higher risk of injury or lead to negative impacts on their overall performance levels. This research in chapter seven compared self-reported subjective measures from the players themselves. Additional data (RSImod) were provided via objective standardised testing by the professional performance staff.

The final dataset was gathered using a noninvasive biopotentials measure which estimated the overall functional state of the central nervous system of the players. In turn, these alterations could detect changes in an players overall functional state. Needless to say, biopotential measures would not replace existing subjective and objective metrics but could be used in conjunction with these measures to objectively monitor activity levels. Familiarity with subjective self-reported measures (POMS) in this research did not seem to adequately reflect the wellbeing of the players. RSImod, even though it is a valid and reliable measure of neuromuscular fatigue, the addition of another measure such as biopotentials may offer a more comprehensive account of overall player wellbeing.

The final chapter in this thesis, addressed an ever-present challenge for amateur coaches who coach amateur adolescent rugby players. In many amateur rugby clubs, the predominant source of coaches are volunteers who may or may not have much exposure to formal rugby coaching resources. Under these circumstances, it can be difficult to standardize rugby coaching practice. As rugby is a collision sport, where contact is frequently occurring between players, it's essential that players develop suitable contact skills such as tackle technique. Tackling in rugby is a central part of the game, however, it is a highly technical skill for any coach to convey to players in a safe and efficient manner. The main purpose of tackling is to halt opposition progress while remaining as safe from injury risk (i.e., concussion, cuts, and abrasions) as is feasible. With respect to this, chapter eight sought to develop a novel coaching platform for practical use by amateur coaches in amateur club settings.

There are multiple different types of tackle and there are many different approaches to coach safe technique to younger players. The broadly accepted practice of coaching players to approach a tackle contest with their torso angled parallel to the playing surface. This posture should be attempted while maintaining forward momentum to tackle the opposing player. This enables the tackler to see their opposing player and ensure that they keep their head up and theoretically in a safer position. The primary coaching point is that players should attempt to be able to see the oncoming opposing player and execute safer contact by maintaining a zero angle of approach to the opposing player. The coaching platform detailed in chapter eight used IMUs and a novel mobile application that could constitute part of an injury reduction system for novice and/or inexperienced amateur coaches.

9.2 - Limitations

There are limitations throughout this thesis, in a certain manner, this reflects the evolution of concussion research over the previous number of years. New research is emerging at an accelerated rate, which in turn reveals the limitations within the current research contained in these chapters. In chapter two the inclusion of research involving lab-based clinical assessments was a limitation. This in parallel with the rules or laws of many sports not having the facility to assess head injury during game time. This limitation would directly affect the timely removal of participants from the sports setting and delay identification of a suspected concussion. The substantial limitation in chapter three revolves around the search strategy which only included adult populations and excluded participants under eighteen years of age. A further limitation of the research in chapter three was the exclusion of studies that had a combination of populations which included participants over the age of eighteen and under the age of eighteen in the same study.

The noteworthy limitation in chapter four were the absence of female participants from the interviews that were conducted. This is a notable limitation across chapters four, five and chapter six, even though every effort was made to recruit females for these studies, none volunteered for the study. Reiterating a similar limitation as found in earlier chapters, the data gathered for this study were recorded from players that had retired in the last ten years. It must be acknowledged that the management of concussions in the professional game has evolved in the interim period and these data may not be best practice in current professional rugby union organisations. It must be noted that there was an impact on gathering data the for the players' voice research in chapters four, five and six. The interviews had a profound effect on the primary researcher. This impact may have affected the interpretation of the data as well as their former experience of being involved in a professional rugby union organisation.

The case study in chapter seven used biopotentials as a possible measure to manage player workload and neuromuscular fatigue. However, it is not possible to claim that neurological function could be used as a standalone measure. Even though the use of biopotentials appeared to be more perceptive to alterations in the players' functional state. Another limitation was the six-week duration of the test period and the number of participants included in the study. The test period was overly brief to determine whether biopotentials could be a useful objective measure. The main limitation were the algorithms used in the technology itself, these limitations were undetermined due to the proprietorship of the device manufacturer.

The research is chapter eight was a proof-of-concept, in this regard the study would require additional development and testing to deliver a more robust coaching platform. Testing the mobile application solely used static tackle technique which may not reflect real world scenarios regarding tackles in live rugby contests. As this platform was primarily developed for younger players, it is unknown how this platform would function with adult players. In conjunction with these elements, a final limitation of the concept was that all participants were male. With respect to this, it is uncertain whether the coaching platform could be utilised for female rugby players due to differences in anthropometrics between male and female players.

9.3 – Original Contributions

The contributions to the research area in chapter two centered on identifying the notable absence of pitch side concussion testing in community and amateur sport. This highlighted the dearth of concussion education at the community and amateur levels of sport. In practice at these levels, the people responsible for removing athletes from play who have a suspected concussion may be untrained volunteer coaches or sports officials. For many practitioners, the anecdotal inclusion of neck strength training to strength and conditioning programmes has been viewed as a mitigating factor against head injury and concussion. The research in chapter three demonstrated the lack of evidence to suggest that neck strength could be utilized in this manner. The current evidence remains hypothetical in relation to any long-term mitigating benefits of developing neck strength to reduce head and neck injury including concussion.

Chapters four, five and six provided an opportunity to gather data from ex-professional rugby players on a range of topics. Interviews from a cohort of participants from a number of different countries are uncommon, in that sense, the data that were provided offered unique insights into professional rugby union players. The data derived from these chapters provided insights about how dismissive rugby players were about concussion and the short-term view they had about their health and wellbeing. Consequently, these players expressed concerns about their long-term health as they felt they were treated as commodities within professional clubs. Their opinions about safety equipment and how professional rugby organisations should have an ongoing duty of care towards retired players were noteworthy contributions to the literature.

The use of biopotentials to monitor player neuromuscular state as part of a workload management strategy was highly novel in the realm of rugby union. The use of this technology appeared to be more sensitive to managing players wellbeing and demonstrated potential for future use a monitoring tool in this respect. The development of a bespoke novel coaching platform to assist amateur coaches involved with younger amateur rugby players showed that it is possible to use IMUs to coach suitable and safe body angles when approaching tackle contests. The accessibility to these types of mobile applications and IMU technology suggests that the platform could have widespread use in the amateur levels of rugby union.

9.4 – Future Directions

There are multiple future directions for advancing research in concussion identification, management, and potential mitigation strategies. The shortage of adequate pitch side identification and testing for concussion in amateur sports in a large area for development. Concussion education and knowledge retention for amateur club coaches and/or officials to identify when a concussion occurs requires further investigation. The current amateur sports concussion landscape has underreporting due primarily to a lack of knowledge of concussion identification which urgently needs to be addressed.

Common to both the amateur and professional sports are the potential benefits of emerging technologies such as smart gumshields and known technologies involving biomarkers. The use of smart instrumented mouthguards to detect impacts and monitor workload for players at all levels could provide useful metrics. Where impacts and measured and known could provide individualised data for a comprehensive player welfare management strategy. Biomarkers are well established to detect brain derived proteins in the bloodstream. These biomarkers require refinement before they could be widely used in concussion detection and diagnosis.

In addition to biomarkers, development of more accurate eye tracking technology is warranted. The use of horizontal and vertical saccadic eye tracking technology as a diagnostic tool for concussion has been well established. However more rigorous testing and standardisation is required before it is widely used in amateur or community sports. Female concussion in the elite and amateur levels of rugby union is currently grossly unresearched. Many of the current assumptions with respect to concussion in female athletes has been derived from male sports. There's a shortfall of available evidence about female concussion regarding identification, symptomology, and recovery.

Practical areas that warrant further investigation include additional longitudinal research towards the efficacy of neck strength and neck girth enhancement to mitigate against concussion risk. Another current area of interest are the discussions around safe tackle height in the amateur and professional game. There is much debate about the optimum level of tackle height, the consensus revolves around safety for the tackler during contact and safety for the individual being tackled during impact. This area requires implementable and appropriate guidelines from governing bodies for the amateur game and for the professional game.

References

Adesida Y, Papi E, McGregor AH. Exploring the role of wearable technology in sport kinematics and kinetics: A systematic review. Sensors. 2019 Apr 2;19(7):1597.

Albert E. Dealing with danger: The normalization of risk in cycling. Int Rev Sport Sociol. 1999 Jun;34(2):157-71.

Amayo J, Tierney GJ. Does tackle height influence offload success in rugby union? Analysis from the 2019 Rugby World Cup. Int J Sports Sci Coach. 2021 Apr;16(2):415-20.

Arbogast KB, Curry AE, Metzger KB, Kessler RS, Bell JM, Haarbauer-Krupa J, Zonfrillo MR, Breiding MJ, Master CL. Improving primary care provider practices in youth concussion management. Clin Pediatr. 2017 Aug;56(9):854-65.

Archbold HA, Rankin AT, Webb M, Nicholas R, Eames NW, Wilson RK, Henderson LA, Heyes GJ, Bleakley CM. RISUS study: rugby injury surveillance in ulster schools. Br J Sports Med. 2017 Apr 1;51(7):600-6.

Aubry M, Cantu R, Dvorak J, Graf-Baumann T, Johnston K, Kelly J, Lovell M, McCrory P, Meeuwisse W, Schamasch P. Summary and agreement statement of the first International Conference on Concussion in Sport, Vienna 2001. Phys Sportsmed. 2002 Feb 1;30(2):57-63.

Baker JF, Devitt BM, Green J, McCarthy C. Concussion among under 20 rugby union players in Ireland: incidence, attitudes and knowledge. Ir J Med Sci. 2013 Mar;182(1):121-5.

Barden C, Stokes K. Epidemiology of injury in elite English Schoolboy rugby Union: a 3-year study comparing different competitions. J Athl Train. 2018 May;53(5):514-20.

Bennett B, Fyall G. Power and control in school Rugby: An hermeneutic interpretation of the pedagogical intentions of five secondary school rugby coaches in New Zealand. J Glob Sport Manag. 2018 Jul 3;3(3):284-301.

Bevan T, Chew S, Godsland I, Oliver NS, Hill NE. A game for all shapes and sizes? Changes in anthropometric and performance measures of elite professional rugby union players 1999–2018. BMJ Open Sport Exerc Med. 2022 Feb 1;8(1):e001235.

Biernacki P, Waldorf D. Snowball sampling: problem and of using nonrandom sampling methodologies. Sociol Methodol. 1981;10:141-63.

Blackett AD, Evans AB, Piggott D. “Active” and “passive” coach pathways: Elite athletes’ entry routes into high-performance coaching roles. Int. Sport Coach. 2018 Sep 1;5(3):213-26.

Block CK, West SE, Goldin Y. Misconceptions and misattributions about traumatic brain injury: An integrated conceptual framework. PM&R. 2016 Jan 1;8(1):58-68.

Blumbergs PC, Scott G, Manavis J, Wainwright H, Simpson DA, McLean AJ. Stalning af amyloid precursor protein to study axonal damage in mild head Injury. The Lancet. 1994 Oct 15;344(8929):1055-6.

Boullosa D, Casado A, Claudino JG, Jiménez-Reyes P, Ravé G, Castaño-Zambudio A, Lima-Alves A, de Oliveira Jr SA, Dupont G, Granacher U, Zouhal H. Do you play or do you train? Insights from individual sports for training load and injury risk management in team sports based on individualization. Front Physiol. 2020 Aug 21;11:995.

Braun V, Clarke V. Using thematic analysis in psychology. Qual Res Psychol. 2006 Jan 1;3(2):77-101.

Braun V. Clarke V. Reflecting on reflexive thematic analysis. Qual Res Sport Exerc Health. 2019 Aug 8;11(4):589-97.

Braun V, Clarke V. To saturate or not to saturate? Questioning data saturation as a useful concept for thematic analysis and sample-size rationales. Qual Res Sport Exerc Health. 2021 Mar 4;13(2):201-16.

Brazier J, Antrobus M, Stebbings GK, Day SH, Callus P, Erskine RM, Bennett MA, Kilduff LP, Williams AG. Anthropometric and physiological characteristics of elite male rugby athletes. J Strength Cond Res. 2020 Jun 1;34(6):1790-801.

Broglio SP, Harezlak J, Katz B, Zhao S, McAllister T, McCrea M. Acute sport concussion assessment optimization: a prospective assessment from the CARE consortium. Sports Med. 2019 Dec;49(12):1977-87.

Buckland ME, Sy J, Szentmariay I, Kullen A, Lee M, Harding A, Halliday G, Suter CM. Chronic traumatic encephalopathy in two former Australian National Rugby League players. Acta Neuropathol Commun. 2019 Dec;7(1):1-4.

Buckley TA, Oldham JR, Munkasy BA, Evans KM. Decreased anticipatory postural adjustments during gait initiation acutely post-concussion. Arch Phys Med Rehabil. 2017 Oct 1;98(10):1962-8.

Burger N, Lambert MI, Viljoen W, Brown JC, Readhead C, Den Hollander S, Hendricks S. Mechanisms and factors associated with tackle-related injuries in South African youth rugby union players. Am J Sports Med. 2017 Feb;45(2):278-85.

Burger N, Lambert M, Hendricks S. Lay of the land: narrative synthesis of tackle research in rugby union and rugby sevens. BMJ Open Sport Exerc Med. 2020 Apr 1;6(1):e000645.

Burlot F, Richard R, Joncheray H. The life of high-level athletes: The challenge of high performance against the time constraint. Int Rev Sociol Sport. 2018 Mar;53(2):234-49.

Caetano Júnior PC, Castilho ML, Raniero L. Salivary cortisol responses and session ratings of perceived exertion to a rugby match and fatigue test. Percept Mot Skills. 2017 Jun;124(3):649-61.

Caddick N, Ryall E. The social construction of 'mental toughness'–a fascistoid ideology? J. Philos. Sport. 2012 May 1;39(1):137-54.

Chambers RM, Gabbett TJ, Cole MH. Validity of a microsensor-based algorithm for detecting scrum events in rugby union. Int J Sports Physiol Perform. 2019 Feb 1;14(2):176-82.

Churchill, N. W., Hutchison, M. G., Graham, S. J., & Schweizer, T. A. (2018). Connectomic markers of symptom severity in sport-related concussion: Whole-brain analysis of resting-state fMRI. Neuroimage: clinical, 18, 518-526.

Churchill N, Hutchison M, Richards D, Leung G, Graham S, Schweizer TA. Brain structure and function associated with a history of sport concussion: a multi-modal magnetic resonance imaging study. J Neurotrauma. 2017 Feb 15;34(4):765-71.

Clacy A, Goode N, Sharman R, Lovell GP, Salmon P. A systems approach to understanding the identification and treatment of sport-related concussion in community rugby union. Appl Ergon. 2019 Oct 1;80:256-64.

Clarke V, Braun V. Successful qualitative research: A practical guide for beginners. Successful Qualitative Research. 2013:1-400.

Clarke V, Braun V, Hayfield N. Thematic analysis. Qual Psychol. 2015 Jan 1;222(2015):248.

Collins CL, Fletcher EN, Fields SK, Kluchurosky L, Rohrkemper MK, Comstock RD, Cantu RC. Neck strength: a protective factor reducing risk for concussion in high school sports. The journal of primary prevention. 2014 Oct;35(5):309-19.

Collins MW, Kontos AP, Reynolds E, Murawski CD, Fu FH. A comprehensive, targeted approach to the clinical care of athletes following sport-related concussion. Knee Surg Sports Traumatol Arthrosc. 2014 Feb;22(2):235-46.

Collins, T. *A social history of English rugby union*. Routledge, United Kingdom, 2009

Collins, T. How football began: A global history of how the world's football codes were born. Routledge, United Kingdom, 2018.

Conway F, Domingues M, Monaco R, Lesnewich LM, Ray AE, Alderman BL, Todaro SM, Buckman JF. Concussion symptom underreporting among incoming NCAA Division I college athletes. Clin J Sport Med. 2018 Jan 10.

Covassin T, Elbin RJ, Crutcher B, Burkhart S. The management of sport-related concussion: considerations for male and female athletes. Transl Stroke Res. 2013 Aug;4(4):420-4.

Covassin, T.; Savage, J.L.; Bretzin, A.C.; Fox, M.E. Sex differences in sport-related concussion long-term out-comes. Int. J. Psychophysiol. 2018, 132, 9–13.

Cross MJ, Tucker R, Raftery M, Hester B, Williams S, Stokes KA, Ranson C, Mathema P, Kemp S. Tackling concussion in professional rugby union: a case–control study of tackle-based risk factors and recommendations for primary prevention. Br J Sports Med. 2019 Aug 1;53(16):1021-5.
Cross MJ, Tucker R, Raftery M, Hester B, Williams S, Stokes KA, Ranson C, Mathema P, Kemp S. Tackling concussion in professional rugby union: a case–control study of tackle-based risk factors and recommendations for primary prevention. Br J Sports Med. 2019 Aug 1;53(16):1021-5.
Cross MJ, Williams S, Trewartha G, Kemp SP, Stokes KA. The influence of in-season training loads on injury risk in professional rugby union. Int J Sports Physiol Perform. 2016 Apr 1;11(3):350-5.

Cunningham J, Broglio S, Wyse J, Mc Hugh C, Farrell G, Denvir K, Wilson F. Athlete concussion history recall is underestimated: A validation study of self-reported concussion history among current professional rugby union players. Brain Inj. 2021 Jan 5;35(1):65-71.

Curry TJ. A little pain never hurt anyone: Athletic career socialization and the normalization of sports injury. Symb Interact. 1993 Sep;16(3):273-90.

Cust EE, Sweeting AJ, Ball K, Robertson S. Machine and deep learning for sport-specific movement recognition: A systematic review of model development and performance. J Sports Sci. 2019 Mar 4;37(5):568-600.

Daly E, Pearce AJ, Blackett AD, Ryan L. Injury as an occupational hazard in professional rugby union: A qualitative analysis of interviews with ex-professional rugby players. J Sports Sci. 2022 Jan 8.

Daly E, White A, Blackett AD, Ryan L. Pressure. a qualitative analysis of the perception of concussion and injury risk in retired professional rugby players. J Funct Morphol. 2021 Sep 21;6(3):78.

Davidow D, Quarrie K, Viljoen W, Burger N, Readhead C, Lambert M, Jones B, Hendricks S. Tackle technique of rugby union players during head impact tackles compared to injury free tackles. J Sci Med Spor. 2018 Oct 1;21(10):1025-31.

Davidow D, Redman M, Lambert M, Burger N, Smith M, Jones B, Hendricks S. The effect of physical fatigue on tackling technique in Rugby Union. J Sci Med Sport. 2020 Nov 1;23(11):1105-10.

Davis GA, Makdissi M, Bloomfield P, Clifton P, Echemendia RJ, Falvey ÉC, Fuller GW, Green G, Harcourt P, Hill T, McGuirk N. International consensus definitions of video signs of concussion in professional sports. Br J Sports Med. 2019 Oct 1;53(20):1264-7.

Davis-Hayes C, Gossett JD, Levine WN, Shams T, Harada J, Mitnick J, Noble J. Sex-specific outcomes and predictors of concussion recovery. J Am Acad Orthop Surg. 2017 Dec 1;25(12):818-28.

Davis GA, Anderson V, Babl FE, Gioia GA, Giza CC, Meehan W, Moser RS, Purcell L, Schatz P, Schneider KJ, Takagi M. What is the difference in concussion management in children as compared with adults? A systematic review. Br J Sports Med. 2017 Jun 1;51(12):949-57.

Delic V, Beck KD, Pang KC, Citron BA. Biological links between traumatic brain injury and Parkinson's disease. Acta Neuropathol Commun. 2020 Dec;8(1):1-6.

Desai N, Wiebe DJ, Corwin DJ, Lockyer JE, Grady MF, Master CL. Factors affecting recovery trajectories in paediatric female concussion. Clin J Sport Med. 2019 Sep 1;29(5):361-7.

Dettwiler A, Murugavel M, Putukian M, Cubon V, Furtado J, Osherson D. Persistent differences in patterns of brain activation after sports-related concussion: a longitudinal functional magnetic resonance imaging study. J Neurotrauma. 2014 Jan 15;31(2):180-8.

den Hollander S, Lambert M, Jones B, Hendricks S. Tackle and ruck technique proficiency within academy and senior club rugby union. J Sports Sci. 2019 Nov 17;37(22):2578-87.

den Hollander S, Lambert M, Jones B, Hendricks S. Tackle technique knowledge alone does not translate to proper tackle technique execution in training. BMJ Open Sport Exerc Med. 2021 Mar 1;7(1):e001011.

Di Battista AP, Churchill N, Rhind SG, Richards D, Hutchison MG. The relationship between symptom burden and systemic inflammation differs between male and female athletes following concussion. BMC Immunol. 2020 Dec;21(1):1-1.

Di Virgilio TG, Letswaart M, Wilson L, Donaldson DI, Hunter AM. Understanding the consequences of repetitive subconcussive head impacts in sport: brain changes and dampened motor control are seen after boxing practice. Frontiers in human neuroscience. 2019 Sep 10;13:294.

Dimou S, Lagopoulos J. Toward objective markers of concussion in sport: a review of white matter and neurometabolic changes in the brain after sports-related concussion. J Neurotrauma. 2014 Mar 1;31(5):413-24.

Di Pietro V, O'Halloran P, Watson CN, Begum G, Acharjee A, Yakoub KM, Bentley C, Davies DJ, Iliceto P, Candilera G, Menon DK. Unique diagnostic signatures of concussion in the saliva of male athletes: the Study of Concussion in Rugby Union through MicroRNAs (SCRUM). Br J Sports Med. 2021 Dec 1;55(24):1395-404.

D'Lauro C, Johnson BR, McGinty G, Allred CD, Campbell DE, Jackson JC. Reconsidering return-to-play times: a broader perspective on concussion recovery. Orthop J Sports Med. 2018 Mar 9;6(3):2325967118760854.

Doucette MM, Du Plessis S, Webber AM, Whalen C, Garcia-Barrera MA. In it to win it: Competitiveness, concussion knowledge and nondisclosure in athletes. The Physician and Sports Medicine. 2021 Apr 3;49(2):194-202.

Douglas K, Carless D. Life story research in sport: Understanding the experiences of elite and professional athletes through narrative. Routledge; 2014 Dec 17.

Downs SH, Black N. The feasibility of creating a checklist for the assessment of the methodological quality both of randomised and non-randomised studies of health care interventions. J Epidemiol Community Health. 1998 Jun 1;52(6):377-84.

Downey RI, Hutchison MG, Comper P. Determining sensitivity and specificity of the Sport Concussion Assessment Tool 3 (SCAT3) components in university athletes. Brain Inj. 2018 Sep 19;32(11):1345-52.

Draper N, Kabaliuk N, Stitt D, Alexander K. Potential of soft-shelled rugby headgear to reduce linear impact accelerations. J Healthc Eng. 2021 Apr 23;2021.

Dubois R, Lyons M, Paillard T, Maurelli O, Prioux J. Influence of weekly workload on physical, biochemical and psychological characteristics in professional rugby union players over a competitive season. J Strength Cond Res. 2020 Feb 1;34(2):527-45.

Eagle SR, Kontos AP, Pepping GJ, Johnson CD, Sinnott A, LaGoy A, Connaboy C. Increased risk of musculoskeletal injury following sport-related concussion: a perception–action coupling approach. Sports Med. 2020 Jan;50(1):15-23.

Echemendia RJ, Ahmed OH, Bailey CM, Bruce JM, Burma JS, Davis GA, Gioia G, Howell D, Fuller GW, Master CL, van Ierssel J. Introducing the concussion recognition tool 6 (Crt6). British journal of sports medicine. 2023 Jun 1;57(11):689-91.

Echemendia RJ, Broglio SP, Davis GA, Guskiewicz KM, Hayden KA, Leddy JJ, Meehan WP, Putukian M, Sullivan SJ, Schneider KJ, McCrory P. What tests and measures should be added to the SCAT3 and related tests to improve their reliability, sensitivity and/or specificity in sideline concussion diagnosis? A systematic review. Br J Sports Med. 2017 Jun 1;51(11):895-901.

Eckersley CP, Nightingale RW, Luck JF, Bass CR. The role of cervical muscles in mitigating concussion. J Sci Med Sport. 2019 Jun 1;22(6):667-71.

Ellingson LL. Engaging crystallization in qualitative research: An introduction. Sage; 2009.

England Professional Rugby Injury Surveillance Project (2019-20) Available online https://www.englandrugby.com/dxdam/ab/ab1ea449-5915-4c5c-ab27-9f90ed076bd8/PRISP%20report%2019-20%20Final.pdf (accessed July 2023)

Esportif Intelligence, European Rugby by the Numbers, (2018-19), https://esportif.com/

Fallon S, Akhand O, Hernandez C, Galetta MS, Hasanaj L, Martone J, Webb N, Drattell J, Amorapanth P, Rizzo JR, Nolan-Kenney R. MULES on the sidelines: a vision-based assessment tool for sports-related concussion. J Neurol Sci. 2019 Jul 15;402:52-6.

Fields JB, Lameira DM, Short JL, Merrigan JM, Gallo S, White JB, Jones MT. Relationship between external load and self-reported wellness measures across a men's Collegiate soccer preseason. J Strength Cond Res. 2021 May 1;35(5):1182-6.

Flanagan E. The reactive strength index revisited. Train With Push. (2016).

Flanagan EP, Comyns TM. The use of contact time and the reactive strength index to optimize fast stretch-shortening cycle training. J Strength Cond Res. 2008 Oct 1;30(5):32-8.

Fletcher D, Hanton S, Wagstaff CR. Performers' responses to stressors encountered in sport organisations. J Sports Sci. 2012 Feb 1;30(4):349-58.

Fraas MR, Coughlan GF, Hart EC, McCarthy C. Concussion history and reporting rates in elite Irish rugby union players. Phys Ther Sport. 2014 Aug 1;15(3):136-42.

Fraas MR, Burchiel J. A systematic review of education programmes to prevent concussion in rugby union. Eur J Sport Sci. 2016 Nov 16;16(8):1212-8.

Fuller GW, Cross MJ, Stokes KA, Kemp SP. King-Devick concussion test performs poorly as a screening tool in elite rugby union players: a prospective cohort study of two screening tests versus a clinical reference standard. Br J Sports Med. 2019 Dec 1;53(24):1526-32.

Fuller CW, Fuller GW, Kemp SP, Raftery M. Evaluation of World Rugby's concussion management process: results from Rugby World Cup 2015. Br J Sports Med. 2017 Jan 1;51(1):64-9.

Fuller GW, Kemp SP, Decq P. The International Rugby Board (IRB) pitch side concussion assessment trial: a pilot test accuracy study. Br J Sports Med. 2015 Apr 1;49(8):529-35.

Fuller CW, Taylor AE, Raftery M. Should player fatigue be the focus of injury prevention strategies for international rugby sevens tournaments? Br J Sports Med. 2016 Jun 1;50(11):682-7.

Gaelic Player Association (Acquired Brain Injury Ireland) 2012 - https://data.oireachtas.ie/ie/oireachtas/committee/dail/31/joint_committee_on_education_and_social_protection/reports/2014/2014-12-17_report-on-concussion-in-sport_en.pdf (accessed July 2020)

Gagnon I. Determining outcome in children and adolescents after concussion: viewing things more holistically. J Orthop Sports Phys Ther. 2019 Nov;49(11):855-63.

Galetta KM, Morganroth J, Moehringer N, Mueller B, Hasanaj L, Webb N, Civitano C, Cardone DA, Silverio A, Galetta SL, Balcer LJ. Adding vision to concussion testing: a prospective study of sideline testing in youth and collegiate athletes. J Neuro-Ophthalmol. 2015 Sep 1;35(3):235-41.

Gardner AJ, Iverson GL, Quinn TN, Makdissi M, Levi CR, Shultz SR, Wright DK, Stanwell P. A preliminary video analysis of concussion in the National Rugby League. Brain Inj. 2015 Aug 24;29(10):1182-5.

Geary K, Green BS, Delahunt E. Effects of neck strength training on isometric neck strength in rugby union players. Clin J Sport Med. 2014 Nov 1;24(6):502-8.

Ghattas J, Jarvis DN. Validity of inertial measurement units for tracking human motion: a systematic review. Sports Biomech. 2021 Oct 28:1-4.

Giazitzoglu A. This Sporting Life: The intersection of hegemonic masculinities, space, and emotions among rugby players. Gend. Work Organ.2020 Jan;27(1):67-81.

Gilchrist I, Storr M, Chapman E, Pelland L. Neck Muscle Strength Training in the Risk Management of Concussion in Contact Sports: Critical Appraisal of Application to Practice. J. Athl. Enhanc 4: 2. of. 2015;19:2.

Goble DJ, Manyak KA, Abdenour TE, Rauh MJ, Baweja HS. An initial evaluation of the BTrackS balance plate and sports balance software for concussion diagnosis. Int J Sports Phys Ther. 2016 Apr;11(2):149.

Grainger A, Heffernan S, Waldrom M, Sawczuk T. Autonomic Nervous System Indices of Player Readiness During Elite-Level Rugby Union Game-Week Microcycles. J Strength Cond Res. 2022 May 9:10-519.

Graves BS. University football players, postural stability, and concussions. J Strength Cond Res. 2016 Feb 1;30(2):579-83.

Grandou C, Wallace L, Impellizzeri FM, Allen NG, Coutts AJ. Overtraining in resistance exercise: an exploratory systematic review and methodological appraisal of the literature. Sports Med. 2020 Apr;50(4):815-28.

Griffin A, Kenny IC, Comyns TM, Lyons M. Training load monitoring in amateur rugby union: a survey of current practices. The Journal of Strength & Conditioning Research. 2021 Jun 1;35(6):1568-75.

Haas LF. Hans berger (1873–1941), richard caton (1842–1926), and electroencephalography. J Neurol. Neurosurg Psychiatry. 2003 Jan 1;74(1):9-.

Hamlin, M. J., Deuchrass, R. W., Elliot, C. E., & Manimmanakorn, N. Short and long-term differences in anthropometric characteristics and physical performance between male rugby players that became professional or remained amateur. J Exerc Sci Fit 2021, 19(3), 143-149.

Hamlin MJ, Wilkes D, Elliot CA, Lizamore CA, Kathiravel Y. Monitoring training loads and perceived stress in young elite university athletes. Front Physiol. 2019 Jan 29;10:34.

Handu D, Moloney L, Wolfram T, Ziegler P, Acosta A, Steiber A. Academy of Nutrition and Dietetics methodology for conducting systematic reviews for the Evidence Analysis Library. J Acad Nutr Diet. 2016 Feb;116(2):311-8.

Hänninen T, Parkkari J, Tuominen M, Öhman J, Howell DR, Iverson GL, Luoto TM. Sport Concussion Assessment Tool: Interpreting day-of-injury scores in professional ice hockey players. J Sci Med Sport. 2018 Aug 1;21(8):794-9.

Harris, S.A., et al., Do Side-line Tests of Vestibular and Oculomotor Function Accurately Diagnose Sports-Related Concussion in Adults? A Systematic Review and Meta-analysis. Am J Sports Med. 2021: p. 3635465211027946.

Harriss AB, Abbott KC, Humphreys D, Daley M, Moir ME, Woehrle E, Balestrini CS, Fischer LK, Fraser DD, Shoemaker JK. Concussion symptoms predictive of adolescent sport-related concussion injury. Clin J Sport Med. 2020 Sep 1;30(5):e147-9.

Harrold GK, Hasanaj L, Moehringer N, Zhang I, Nolan R, Serrano L, Raynowska J, Rucker JC, Flanagan SR, Cardone D, Galetta SL. Rapid sideline performance meets outpatient clinic: results from a multidisciplinary concussion center registry. J Neurol Sci. 2017 Aug 15;379:312-7.

Hawkins RD, Fuller CW. A prospective epidemiological study of injuries in four English professional football clubs. Br J Sports Med. 1999 Jun 1;33(3):196-203.

Hecimovich M, King D, Dempsey AR, Murphy M. The King–Devick test is a valid and reliable tool for assessing sport-related concussion in Australian football: A prospective cohort study. J Sci Med Sport. 2018 Oct 1;21(10):1004-7.

Hellewell SC, Welton T, Pearce AJ, Maller JJ, Grieve SM. Diffusion MRI as a complementary assessment to cognition, emotion, and motor dysfunction after sports-related concussion: a systematic review and critical appraisal of the literature. Brain Imaging Behav. 2021 Jun;15(3):1685-704.

Hendricks S, den Hollander S, Lambert M. Coaching behaviours and learning resources; influence on rugby players' attitudes towards injury prevention and performance in the tackle. Sci Med Footb. 2020a Jan 2;4(1):10-4.

Hendricks S, Matthews B, Roode B, Lambert M. Tackler characteristics associated with tackle performance in rugby union. Eur J Sport Sci. 2014 Nov 17;14(8):753-62.

Hendricks S, O'Connor S, Lambert M, Brown JC, Burger N, Mc Fie S, Readhead C, Viljoen W. Video analysis of concussion injury mechanism in under-18 rugby. BMJ Open Sport Exerc Med. 2016 Sep 1;2(1):e000053.

Hendricks S, Sarembock M, Jones B, Till K, Lambert M. The tackle in South African youth rugby union– Gap between coaches' knowledge and training behaviour. Int J Sports Sci Coach. 2017 Dec;12(6):708-15.

Hendricks S, Till K, Den Hollander S, Savage TN, Roberts SP, Tierney G, Burger N, Kerr H, Kemp S, Cross M, Patricios J. Consensus on a video analysis framework of descriptors and definitions by the Rugby Union Video Analysis Consensus group. Br. J. Sports Med. 2020b May 1;54(10):566-72.

Hendricks S, Till K, Oliver JL, Johnston RD, Attwood M, Brown J, Drake D, MacLeod S, Mellalieu SD, Treu P, Jones B. Technical skill training framework and skill load measurements for the rugby union tackle. J Strength Cond.2018 Oct 1;40(5):44-59.

Hicks SD, Onks C, Kim RY, Zhen KJ, Loeffert J, Loeffert AC, Olympia RP, Fedorchak G, DeVita S, Rangnekar A, Leddy J. Diagnosing mild traumatic brain injury using saliva RNA compared to cognitive and balance testing. Clin Transl Med. 2020 Oct;10(6):e197.

Hill NE, Rilstone S, Stacey MJ, Amiras D, Chew S, Flatman D, Oliver NS. Changes in northern hemisphere male international rugby union players' body mass and height between 1955 and 2015. BMJ Open Sport Exerc Me. 2018 Nov 1;4(1):e000459.

Hind K, Konerth N, Entwistle I, Hume P, Theadom A, Lewis G, King D, Goodbourn T, Bottiglieri M, Ferraces-Riegas P, Ellison A. Mental health and wellbeing of retired elite and amateur rugby players and non-contact athletes and associations with sports-related concussion: the UK Rugby Health Project. Sports medicine. 2021 Nov 18:1-3.

Hind K, Konerth N, Entwistle I, Theadom A, Lewis G, King D, Chazot P, Hume P. Cumulative sport-related injuries and longer-term impact in retired male Elite-and Amateur-Level rugby code athletes and non-contact athletes: a retrospective study. Sports Med. 2020 Nov;50(11):2051-61.

Hollander SD, Ponce C, Lambert M, Jones B, Hendricks S. Tackle and ruck technical proficiency in rugby union and rugby league: A systematic scoping review. Int J Sports Sci Coach. 2021 Apr;16(2):421-34.

Howell DR, Lynall RC, Buckley TA, Herman DC. Neuromuscular control deficits and the risk of subsequent injury after a concussion: a scoping review. Sports Med. 2018 May;48(5):1097-115.

Howell DR, Myer GD, Brilliant A, Foss KB, Meehan III WP. Quantitative multimodal assessment of concussion recovery in youth athletes. Clin J Sport Med. 2021 Mar 1;31(2):133-8.

Hrysomallis C. Neck muscular strength, training, performance and sport injury risk: a review. Sports Med. 2016 Aug;46(8):1111-24.

Hume PA, Theadom A, Lewis GN, Quarrie KL, Brown SR, Hill R, Marshall SW. A comparison of cognitive function in former rugby union players compared with former non-contact-sport players and the impact of concussion history. Sports Med. 2017 Jun;47(6):1209-20.

Hunzinger KJ, Costantini KM, Swanik CB, Buckley TA. Diagnosed concussion is associated with increased risk for lower extremity injury in community rugby players. J Sci Med Sport. 2021 Apr 1;24(4):368-72.

Irish Rugby Football Union, Irish Rugby Injury Surveillance (IRIS) Report 2018-19. Available online: https://www.ul.ie/pess/content/iris-season-reports (accessed July 2020).

https://resources.world.rugby/worldrugby/document/2020/07/28/212ed9cf-cd61-4fa3-b9d4-9f0d5fb61116/P56-57-Participation-Map_v3.pdf

Jacquin A, Kanakia S, Oberly D, Prichep LS. A multimodal biomarker for concussion identification, prognosis and management. Comput Biol Med. 2018 Nov 1;102:95-103.

Jäkel, A. and P. von Hauenschild, *Therapeutic effects of cranial osteopathic manipulative medicine: a systematic review.* Int J Osteopath Med.2011. **111**(12): p. 685-693

Kamins J, Bigler E, Covassin T, Henry L, Kemp S, Leddy JJ, Mayer A, McCrea M, Prins M, Schneider KJ, McLeod TC. What is the physiological time to recovery after concussion? A systematic review. Br. J. Sports Med. 2017 Jun 1;51(12):935-40.

King D, Hume P, Gissane C, Clark T. Semi-professional rugby league players have higher concussion risk than professional or amateur participants: a pooled analysis. Sports Med. 2016 Feb;47(2):197-205.

King D, Gissane C, Hume PA, Flaws M. The King–Devick test was useful in management of concussion in amateur rugby union and rugby league in New Zealand. J Neurol Sci. 2015 Apr 15;351(1-2):58-64.

King R, Grohs MN, Kirton A, Lebel C, Esser MJ, Barlow KM. Microstructural neuroimaging of white matter tracts in persistent post-concussion syndrome: A prospective controlled cohort study. NeuroImage: Clin. 2019 Jan 1;23:101842.

Knight JM, Nguyen JV, Mitra B, Willmott C. Soft-shell headgear, concussion and injury prevention in youth team collision sports: a systematic review. BMJ open. 2021 Jun 1;11(6):e044320.

Kovac S, Speckmann EJ, Gorji A. Uncensored EEG: The role of DC potentials in neurobiology of the brain. Prog Neurobiol. 2018 Jun 1;165:51-65.

Kraak W, Coetzee L, Kruger A, Stewart R, van Vuuren H. Knowledge and attitudes towards concussion in Western Province rugby union senior club rugby players. Int J Sports Med. 2019 Dec;40(13):825-30.

Kroshus E, Baugh CM, Daneshvar DH, Viswanath K. Understanding concussion reporting using a model based on the theory of planned behavior. J Adolesc Health. 2014 Mar 1;54(3):269-74.

Kroshus E, Kubzansky LD, Goldman RE, Austin SB. Norms, athletic identity, and concussion symptom under-reporting among male collegiate ice hockey players: a prospective cohort study. Ann Behav Med. 2015 Feb 1;49(1):95-103.

Kroshus E, Rivara FP, Whitlock KB, Herring SA, Chrisman SP. Disparities in athletic trainer staffing in secondary school sport: implications for concussion identification. Clin J Sport Med. 2017 Nov 1;27(6):542-7.

Kuo C, Wu L, Loza J, Senif D, Anderson SC, Camarillo DB. Comparison of video-based and sensor-based head impact exposure. PloS one. 2018 Jun 19;13(6):e0199238.

Kung SM, Suksreephaisan TK, Perry BG, Palmer BR, Page RA. The effects of anticipation and visual and sensory performance on concussion risk in sport: A review. Sports Med Open. 2020 Dec;6(1):1-4.

Leahy R, Farrington S, Whyte E, O'Connor S. Concussion reporting, knowledge and attitudes in Irish amateur Gaelic games athletes. Phys Ther Sport. 2020 May 1;43:236-43.

Le Flao E, Brughelli M, Hume PA, King D. Assessing head/neck dynamic response to head perturbation: a systematic review. Sports Med. 2018 Nov;48(11):2641-58.

Leong DF, Balcer LJ, Galetta SL, Evans G, Gimre M, Watt D. The King–Devick test for sideline concussion screening in collegiate football. J Optom. 2015 Apr 1;8(2):131-9.

Leung FT, Franettovich Smith MM, Hides JA. Injuries in Australian school-level rugby union. J Sports Sci. 2017 Nov 2;35(21):2088-92.

Levitch CF, Zimmerman ME, Lubin N, Kim N, Lipton RB, Stewart WF, Kim M, Lipton ML. Recent and long-term soccer heading exposure is differentially associated with neuropsychological function in amateur players. J Int Neuropsychol Soc. 2018 Feb;24(2):147-55.

Lininger MR, Wayment HA, Craig DI, Huffman AH, Lane TS. Improving Concussion-Reporting behavior in national collegiate athletic association division I football players: evidence for the applicability of the Socioecological model for athletic trainers. J Athl Train. 2019 Jan;54(1):21-9.

Liston K, Reacher D, Smith A, Waddington I. Managing pain and injury in non-elite rugby union and rugby league: A case study of players at a British university. Sport Soc. 2006 Jul 1;9(3):388-402.

Livingston G, Huntley J, Sommerlad A, Ames D, Ballard C, Banerjee S, Brayne C, Burns A, Cohen-Mansfield J, Cooper C, Costafreda SG. Dementia prevention, intervention, and care: 2020 report of the Lancet Commission. Lancet. 2020 Aug 8;396(10248):413-46.

Longworth T, McDonald A, Cunningham C, Khan H, Fitzpatrick J. Do rugby league players under-report concussion symptoms? A cross-sectional study of elite teams based in Australia. BMJ Open Sport Exerc Med. 2021 Jan 1;7(1):e000860.

Mackay, D.F.; Russell, E.R.; Stewart, K.; MacLean, J.A.; Pell, J.P.; Stewart, W. Neurodegenerative Disease Mortality among Former Professional Soccer Players. New Engl. J. Med. 2019, 381, 1801–1808

Madrigal L, Robbins J, Gill DL, Wurst K. A pilot study investigating the reasons for playing through pain and injury: Emerging themes in men’s and women’s collegiate rugby. Sport Psychol. 2015 Dec 1;29(4):310-8.

Malcolm D. Medical uncertainty and clinician–athlete relations: The management of concussion injuries in rugby union. Sociol Sport J. 2009 Jun 1;26(2):191-210.

Malcolm D, Sheard K. " Pain in the Assets": The Effects of Commercialization and Professionalization on the Management of Injury in English Rugby Union. Sociol Sport J. 2002 Jun 1;19(2).

Marinides Z, Galetta KM, Andrews CN, Wilson JA, Herman DC, Robinson CD, Smith MS, Bentley BC, Galetta SL, Balcer LJ, Clugston JR. Vision testing is additive to the sideline assessment of sports-related concussion. Neurol Clin Pract. 2015 Feb 1;5(1):25-34.

Martland HS, Beling CC. Traumatic cerebral haemorrhage. Archives of Neurology & Psychiatry. 1929 Nov 1;22(5):1001-23.

Massey, P. Rugby Union's Late Conversion to Professionalism: An Economic Perspective. The Sage Handbook of Sports Economics, Sage Publications, London, United Kingdom, 2019; pp. 268-278.

Mathema P, Evans D, Moore IS, Ranson C, Martin R. Concussed or not? An assessment of concussion experience and knowledge within elite and semi-professional rugby union. Clin J Sport Med. 2016 Jul 1;26(4):320-5.

Mayer J, Thiel A. Presenteeism in the elite sports workplace: The willingness to compete hurt among German elite handball and track and field athletes. Int Rev Sport Sociol. 2018 Feb;53(1):49-68.

McAllister T, McCrea M. Long-term cognitive and neuropsychiatric consequences of repetitive concussion and head-impact exposure. J Athl Train. 2017 Mar;52(3):309-17.

McCrory P, Meeuwisse W, Dvorak J, Aubry M, Bailes J, Broglio S, Cantu RC, Cassidy D, Echemendia RJ, Castellani RJ, Davis GA. Consensus statement on concussion in sport—the 5th international conference on concussion in sport held in Berlin, October 2016. Br J Sports Med. 2017 Jun 1;51(11):838-47.

McEwen CE, Clarke LH, Bennett EV, Dawson KA, Crocker PR. "It's This Thing of Being an Olympian That You Don't Get From Anything Else": Changing Experiences of Canadian Individual-Sport Athletes With Olympic Team Selection. Sport Psychol. 2018 Jun 1;32(2):81-92.

McGroarty NK, Brown SM, Mulcahey MK. Sport-related concussion in female athletes: A systematic review. Orthop J. Sports Med. 2020 Jul 16;8(7):2325967120932306.

McKee AC, Cantu RC, Nowinski CJ, Hedley-Whyte ET, Gavett BE, Budson AE, Santini VE, Lee HS, Kubilus CA, Stern RA. Chronic traumatic encephalopathy in athletes: progressive tauopathy after repetitive head injury. J Neuropathol Exp Neurol. 2009 Jul 1;68(7):709-35.

McLeod CM, Nite C. Human capital ecosystem construction in an emerging rugby market. J Sport Manag. 2019 Jul 1;33(4):261-74.

McNeel C, Clark GM, Davies CB, Major BP, Lum JA. Concussion incidence and time-loss in Australian football: A systematic review. J Sci Med Sport. 2020 Feb 1;23(2):125-33.

McPherson AL, Nagai T, Webster KE, Hewett TE. Musculoskeletal injury risk after sport-related concussion: a systematic review and meta-analysis. Am. J. Sports Med. 2019 Jun;47(7):1754-62.

Meier TB, Huber DL, Bohorquez-Montoya L, Nitta ME, Savitz J, Teague TK, Bazarian JJ, Hayes RL, Nelson LD, McCrea MA. A prospective study of acute blood-based biomarkers for sport-related concussion. Ann Neurol. 2020 Jun;87(6):907-20.

Melo R, Filgueiras A. Do Depression, Concussion Frequency and Symptoms Differ Between Elite Kickboxers and Amateur Athletes. J Cogn Neuropsychol. 2018;2(1):2.

Merritt, V.C., J.E. Meyer, and P.A. Arnett, A novel approach to classifying post concussion symptoms: The application of a new framework to the Post-Concussion Symptom Scale. J Clin Exp Neuropsychol, 2015. **37**(7): p. 764-75.

Merritt VC, Padgett CR, Jak AJ. A systematic review of sex differences in concussion outcome: what do we know? Clin Neuropsychol. 2019 Aug 18;33(6):1016-43.

Messner MA. When bodies are weapons: Masculinity and violence in sport. Int Rev Sport Sociol. 1990 Sep;25(3):203-20.

Mez J, Daneshvar DH, Kiernan PT, Abdolmohammadi B, Alvarez VE, Huber BR, Alosco ML, Solomon TM, Nowinski CJ, McHale L, Cormier KA. Clinicopathological evaluation of chronic traumatic encephalopathy in players of American football. Jama. 2017 Jul 25;318(4):360-70.

Mihalik JP, Guskiewicz KM, Marshall SW, Greenwald RM, Blackburn JT, Cantu RC. Does cervical muscle strength in youth ice hockey players affect head impact biomechanics? Clin J Sport Med. 2011 Sep 1;21(5):416-21.

Mitra B, Rau TF, Surendran N, Brennan JH, Thaveenthiran P, Sorich E, Fitzgerald MC, Rosenfeld JV, Patel SA. Plasma micro-RNA biomarkers for diagnosis and prognosis after traumatic brain injury: a pilot study. Journal of Clinical Neuroscience. 2017 Apr 1;38:37-42.

Molloy JH, Murphy I, Gissane C. The King–Devick (K–D) test and concussion diagnosis in semi-professional rugby union players. J Sci Med Sport.2017 Aug 1;20(8):708-11.

Moher D, Shamseer L, Clarke M, Ghersi D, Liberati A, Petticrew M, Shekelle P, Stewart LA. Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. Syst Rev. 2015 Dec;4(1):1-9.

Montgomery C, Hurley E, Beirne C, Moran C. Concussion in Rugby Union–A systematic review of knowledge, attitudes and experiences. J Sports Sci Med.2018 Nov 1;21:S23.

Moran RN, Covassin T, Elbin RJ. Sex differences on vestibular and ocular motor assessment in youth athletes. J Athl Train. 2019 Apr;54(4):445-8.

Moreau MS, Langdon JL, Buckley TA. The lived experience of an in-season concussion amongst NCAA Division I student-athletes. Int J Exerc Sci. 2014;7(1):8.

Naish R, Burnett A, Burrows S, Andrews W, Appleby B. Can a specific neck strengthening program decrease cervical spine injuries in a men's professional rugby union team? A retrospective analysis. J Sports Sci Med. 2013 Sep;12(3):542.

Nauright J, Collins T. The rugby world in the professional era. London: Routledge; 2017 Feb 17.

Neidecker J, Sethi NK, Taylor R, Monsell R, Muzzi D, Spizler B, Lovelace L, Ayoub E, Weinstein R, Estwanik J, Reyes P. Concussion management in combat sports: consensus statement from the Association of Ringside Physicians. Br. J. Sports Med. 2019 Mar 1;53(6):328-33.

Nilsson M, Hägglund M, Ekstrand J, Waldén M. Head and neck injuries in professional soccer. Clinical J Sports Med. 2013 Jul 1;23(4):255-60.

Nixon HL. Accepting the risks of pain and injury in sport: Mediated cultural influences on playing hurt. Sociol. Sport J. 1993 Jun 1;10(2):183-96.

Nordström A, Nordström P, Ekstrand J. Sports-related concussion increases the risk of subsequent injury by about 50% in elite male football players. Br. J. Sports Med. 2014 Oct 1;48(19):1447-50.

https://npf.ie/wp-content/uploads/2017/09/0448-GAA.compressed.pdf

O'Connor S, Warrington G, Whelan G, McGoldrick A, Cullen S. Concussion history, reporting behaviors, attitudes, and knowledge in jockeys. Clin J Sport Med. 2020 Nov 1;30(6):578-84.

O'Connor KL, Rowson S, Duma SM, Broglio SP. Head-impact–measurement devices: a systematic review. J Athl Train. 2017 Mar;52(3):206-27.

Oldham JR, Difabio MS, Kaminski TW, Dewolf RM, Howell DR, Buckley TA. Efficacy of Tandem Gait to Identify Impaired Postural Control after Concussion. Med Sci Sports Exerc. 2018 Jun 1;50(6):1162-8.

Owens TS, Calverley TA, Stacey BS, Rose G, Fall L, Tsukamoto H, Jones G, Corkill R, Tuaillon E, Hirtz C, Lehmann S. Concussion history in rugby union players is associated with depressed cerebrovascular reactivity and cognition. Scand J Med Sci Sports. 2021 Dec;31(12):2291-9.

Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, Shamseer L, Tetzlaff JM, Akl EA, Brennan SE, Chou R. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. Syst Rev. 2021 Dec;10(1):1-1.

Patricios, J., et al., What are the critical elements of sideline screening that can be used to establish the diagnosis of concussion? A systematic review. Br J Sports Med. 2017. **51**(11): p. 888-894.

Paul L, Naughton M, Jones B, Davidow D, Patel A, Lambert M, Hendricks S. Quantifying Collision Frequency and Intensity in Rugby Union and Rugby Sevens: A Systematic Review. Sports Med Open. 2022 Dec;8(1):1-38.

Pearce AJ. The neurophysiological response following sub-concussive soccer heading. E Bio Medicine. 2016 Nov 1;13:3-4.

Pearce AJ, Hoy K, Rogers MA, Corp DT, Maller JJ, Drury HG, Fitzgerald PB. The long-term effects of sports concussion on retired Australian football players: a study using transcranial magnetic stimulation. J Neurotrauma. 2014 Jul 1;31(13):1139-45.

Pearce AJ, Hoy K, Rogers MA, Corp DT, Davies CB, Maller JJ, Fitzgerald PB. Acute motor, neurocognitive and neurophysiological change following concussion injury in Australian amateur football. A prospective multimodal investigation. J Sci Med Sport.2015 Sep 1;18(5):500-6.

Pearce AJ, Kidgell DJ, Frazer AK, King DA, Buckland ME, Tommerdahl M. Corticomotor correlates of somatosensory reaction time and variability in individuals with post-concussion symptoms. Somatosens Mot Res. 2020 Jan 2;37(1):14-21.

Pearce AJ, King DA, White AJ, Suter CM. Effects of stricter management guidelines on return-to-competition timeframes following concussion in professional Australian rules football: An exploratory analysis. Sports Med. 2021 Dec;51(12):2647-54.

Pearce AJ, Rist B, Fraser CL, Cohen A, Maller JJ. Neurophysiological and cognitive impairment following repeated sports concussion injuries in retired professional rugby league players. Brain Inj. 2018 Mar 21;32(4):498-505.

Pearce AJ, Sy J, Lee M, Harding A, Mobbs R, Batchelor J, Suter CM, Buckland ME. Chronic traumatic encephalopathy in a former Australian rules football player diagnosed with Alzheimer's disease. Acta Neuropathol Commun. 2020 Dec;8(1):1-4.

Pearce, A.J., M. Tommerdahl, and D.A. King, Neurophysiological abnormalities in individuals with persistent post-concussion symptoms. Neurosci J. 2019. **408**: p. 272-281

Peek RJ, Middleton KJ, Gastin PB, Carey DL, Clarke AC. Position specific peak impact and running demands of professional rugby union players during game play. Int J Sports Sci Coach. 2021 Oct;16(5):1162-8.

Peterson KD. Recurrent neural network to forecast sprint performance. App Artif Intell. 2018 Sep 14;32(7-8):692-706.

Putukian M, Echemendia R, Dettwiler-Danspeckgruber A, Duliba T, Bruce J, Furtado JL, Murugavel M. Prospective clinical assessment using Side-line Concussion Assessment Tool-2 testing in the evaluation of sport-related concussion in college athletes. Clin J Sport Med. 2015 Jan 1;25(1):36-42.

Pringle R, Markula P. No pain is sane after all: A Foucauldian analysis of masculinities and men's rugby experiences of fear, pain, and pleasure. Sociol. Sport J. 2005 Dec 1;22(4):472-97.

Quarrie KL, Hopkins WG. Changes in player characteristics and match activities in Bledisloe Cup rugby union from 1972 to 2004. J Sports Sci. 2007 Jun 1;25(8):895-903.

Quarrie KL, Raftery M, Blackie J, Cook CJ, Fuller CW, Gabbett TJ, Gray AJ, Gill N, Hennessy L, Kemp S, Lambert M. Managing player load in professional rugby union: a review of current knowledge and practices. Br J Sports Med. 2017 Mar 1;51(5):421-7.

Rafferty J, Ranson C, Oatley G, Mostafa M, Mathema P, Crick T, Moore IS. On average, a professional rugby union player is more likely than not to sustain a concussion after 25 matches. Br J Sports Med. 2019 Aug 1;53(15):969-73.

Raftery M, Tucker R, Falvey ÉC. Getting tough on concussion: how welfare-driven law change may improve player safety—a Rugby Union experience. Br J Sports Med. 2021 May 1;55(10):527-9.

Ranaweera J, Weaving D, Zanin M, Roe G. Identifying the Current State and Improvement Opportunities in the Information Flows Necessary to Manage Professional Athletes: A Case Study in Rugby Union. Front Sports Act Living. 2022 Jun 28;4.

Register-Mihalik J, Baugh C, Kroshus E, Y. Kerr Z, Valovich McLeod TC. A multifactorial approach to sport-related concussion prevention and education: application of the socioecological framework. J Athl Train. 2017 Mar;52(3):195-205.

Rizkalla J, Botros D, Alqahtani N, Patnala M, Salama P, Perez FP, Rizkalla M. Eletromagnetic detection of mild brain injury: a novel imaging approach to post concussive syndrome. J Biomed Sci Eng. 2021 Nov;14(11):347.

Roderick M, Waddington I, Parker G. Playing hurt: Managing injuries in English professional football. Int Rev Sport Sociol. 2000 Jun;35(2):165-80.

Rosenbloom C, Broman D, Chu W, Chatterjee R, Okholm Kryger K. Sport-related concussion practices of medical team staff in elite football in the United Kingdom, a pilot study. Sci Med Footb. 2022 Jan 2;6(1):127-35.

Rubenstein R. The Link Between Traumatic Brain Injury and Neurodegenerative Diseases. Neurotrauma: A Comprehensive Textbook on Traumatic Brain Injury and Spinal Cord Injury. 2018 Nov 7:165.

Rugby Football Union, England Professional Rugby Injury Surveillance Project 2017-18 Season Report. 2019. https://www.englandrugby.com//dxdam/96/960006d9-269d-4250-a15f-d9e62f8bfe70/PRISP_1718.pdf (accessed July 2020).

Russell-Giller S, Toto D, Heitzman M, Naematullah M, Shumko J. Correlating the King-Devick test with vestibular/ocular motor screening in adolescent patients with concussion: a pilot study. Sports Health. 2018 Jul;10(4):334-9.

Russell ER, Mackay DF, Lyall D, Stewart K, MacLean JA, Robson J, Pell JP, Stewart W. Neurodegenerative disease risk among former international rugby union players. Journal of Neurology, Neurosurgery & Psychiatry. 2022 Dec 1;93(12):1262-8.

Ruston SW, Kamrath JK, Zanin AC, Posteher K, Corman SR. Performance versus safety: Understanding the logics of cultural narratives influencing concussion reporting behaviors. Commun Sport. 2019 Aug;7(4):529-48.

Safai P. Healing the body in the "culture of risk": Examining the negotiation of treatment between sport medicine clinicians and injured athletes in Canadian intercollegiate sport. Sociol. Sport J. 2003 Jun 1;20(2):127-46.

Salmon DM, Romanchuk J, Sullivan SJ, Walters S, Clacy A, Register-Mihalik JK, Kerr ZY, Whatman C, Keung S. Concussion knowledge, attitude and reporting intention in rugby coaches and high school rugby players. Int J Sports Sci Coach. 2021 Feb;16(1):54-69.

Sanderson J, Weathers M, Snedaker K, Gramlich K. "I was able to still do my job on the field and keep playing": An investigation of female and male athletes' experiences with (not) reporting concussions. Commun Sport. 2017 Jun;5(3):267-87.

Saw AE, Kellmann M, Main LC, Gastin PB. Athlete self-report measures in research and practice: considerations for the discerning reader and fastidious practitioner. Int J Sports Physiol Perform. 2017 Apr 1;12(s2):S2-127.

Schlegel P, Novotny M, Valis M, Klimova B. Head injury in mixed martial arts: a review of epidemiology, affected brain structures and risks of cognitive decline. Phys Sportsmed. 2021 Oct 2;49(4):371-80.

Schlipsing M, Salmen J, Tschentscher M, Igel C. Adaptive pattern recognition in real-time video-based soccer analysis. J Real Time Image Process. 2017 Jun;13(2):345-61.

Scott E, Kidgell DJ, Frazer AK, Pearce AJ. The neurophysiological responses of concussive impacts: a systematic review and meta-analysis of transcranial magnetic stimulation studies. Front Hum Neurosci. 2020 Aug 27;14:306.

Seidman DH, Burlingame J, Yousif LR, Donahue XP, Krier J, Rayes LJ, Young R, Lilla M, Mazurek R, Hittle K, McCloskey C. Evaluation of the King–Devick test as a concussion screening tool in high school football players. J Neurol Sci. 2015 Sep 15;356(1-2):97-101.

Seshadri DR, Li RT, Voos JE, Rowbottom JR, Alfes CM, Zorman CA, Drummond CK. Wearable sensors for monitoring the internal and external workload of the athlete. NPJ Digit Med. 2019 Jul 29;2(1):1-8.

Sherry NS, Fazio-Sumrok V, Sufrinko A, Collins MW, Kontos AP. Multimodal assessment of sport-related concussion. Clin J Sport Med. 2021 May 1;31(3):244-9.

Smulligan KL, Wilson JC, Howell DR. Increased Risk of Musculoskeletal Injuries After Concussion. Operative Techniques in Sports Med. 2022 Mar 1;30(1):150896.

Sobue S, Kawasaki T, Hasegawa Y, Shiota Y, Ota C, Yoneda T, Tahara S, Maki N, Matsuura T, Sekiguchi M, Itoigawa Y. Tackler's head position relative to the ball carrier is highly correlated with head and neck injuries in rugby. Br J Sports Med. 2018 Mar 1;52(6):353-8.

Solomito MJ, Reuman H, Wang DH. Sex differences in concussion: a review of brain anatomy, function, and biomechanical response to impact. Brain inj. 2019 Jan 28;33(2):105-10.

https://www.statista.com/statistics/934866/football-participation-uk/

Sufrinko A, McAllister-Deitrick J, Womble M, Kontos A. Do sideline concussion assessments predict subsequent neurocognitive impairment after sport-related concussion? J Athl Train. 2017 Jul;52(7):676-81.

Sullivan L, Thomas AA, Molcho M. An evaluation of Gaelic Athletic Association (GAA) athletes' self-reported practice of playing while concussed, knowledge about and attitudes towards sports-related concussion. Int J Adolesc Med Health. 2017 Jun 1;29(3).

Sullivan L, Pursell L, Molcho M. Evaluation of a theory-based concussion education program for secondary school student-athletes in Ireland. Health Educ Res. 2018 Dec 1;33(6):492-504.

Sundaram V, Ramachandran AK, Singh U, Pearce AJ. Sex-based differences in concussion incidence and its underlying injury mechanism in team bat/stick sports: A systematic review and meta-analysis. International Journal of Sports Science & Coaching. 2022 Oct 13:17479541221131650.

Sussman ES, Pendharkar AV, Ho AL, Ghajar J. Mild traumatic brain injury and concussion: terminology and classification. Handb Clin Neurol. 2018 Jan 1;158:21-4.

Suter CM, Affleck AJ, Lee M, Pearce AJ, Iles LE, Buckland ME. Chronic traumatic encephalopathy in Australia: the first three years of the Australian Sports Brain Bank. The Medical Journal of Australia. 2022 Jun;216(10):530.

Swart J, Bigard X, Fladischer T, Palfreeman R, Riepenhof H, Jones N, Heron N. Harrogate consensus agreement: Cycling-specific sport-related concussion. SMHS. 2021 Jun 1;3(2):110-4.

Terwilliger VK, Pratson L, Vaughan CG, Gioia GA. Additional post-concussion impact exposure may affect recovery in adolescent athletes. J Neurotrauma. 2016 Apr 15;33(8):761-5.

The Irish Rugby Football Union. (2019). Irish Rugby Football Union Annual Report 2018-2019. https://d2cx26qpfwuhvu.cloudfront.net/irfu/wp-content/uploads/2019/07/18104921/IRFU_AnnualReport_1819.pdf

Tierney GJ, Richter C, Denvir K, Simms CK. Could lowering the tackle height in rugby union reduce ball carrier inertial head kinematics? J Biomech. 2018 Apr 27;72:29-36.

Tierney GJ, Simms CK. Can tackle height influence head injury assessment risk in elite rugby union? J Sci Med Sport. 2018 Dec 1;21(12):1210-4.

Toninato J, Casey H, Uppal M, Abdallah T, Bergman T, Eckner J, Samadani U. Traumatic brain injury reduction in athletes by neck strengthening (TRAIN). Contemp Clin Trials Commun. 2018 Sep 1;11:102-6.

Tucker R, Falvey EC, Fuller GW, Hislop MD, Patricios J, Raftery M. Sport concussion assessment tool: baseline and clinical reference limits for concussion diagnosis and management in elite rugby Union. J Sci Med Sport. 2021 Feb 1;24(2):122-8.

Twist C, Waldron M, Highton J, Burt D, Daniels M. Neuromuscular, biochemical and perceptual post-match fatigue in professional rugby league forwards and backs. J Sports Sci. 2012 Feb 1;30(4):359-67.

Tyson AM, Duma SM, Rowson S. Laboratory evaluation of low-cost wearable sensors for measuring head impacts in sports. J Appl Biomech. 2018 Aug 1;34(4):320-6.

VanItallie TB. Traumatic brain injury (TBI) in collision sports: possible mechanisms of transformation into chronic traumatic encephalopathy (CTE). Metabolism. 2019 Nov 1;100:153943.

Van Ierssel J, Osmond M, Hamid J, Sampson M, Zemek R. What is the risk of recurrent concussion in children and adolescents aged 5–18 years? A systematic review and meta-analysis. Br J Sports Med. 2021 Jun 1;55(12):663-9.

Vartiainen MV, Holm A, Lukander J, Lukander K, Koskinen S, Bornstein R, Hokkanen L. A novel approach to sports concussion assessment: Computerized multilimb reaction times and balance control testing. J Clin Exp Neuropsychol. 2016 Mar 15;38(3):293-307.

Ventura RE, Jancuska JM, Balcer LJ, Galetta SL. Diagnostic tests for concussion: is vision part of the puzzle? J Neuro-Ophthalmol. 2015 Mar 1;35(1):73-81.

Versteegh TH, Dickey JP, Emery CA, Fischer LK, MacDermid JC, Walton DM. Evaluating the effects of a novel neuromuscular neck training device on multiplanar static and dynamic neck strength: a pilot study. J Strength Cond Res. 2020 Mar 1;34(3):708-16.

Viljoen CT, Schoeman M, Brandt C, Patricios J, Van Rooyen C. Concussion knowledge and attitudes among amateur South African rugby players. S. Afr. J. Sports Med. 2017 Sep 20;29(1).

Walshe A, Daly E, Ryan L. Epidemiology of sport-related concussion rates in female contact/collision sport: a systematic review. BMJ Open Sport & Exercise Medicine. 2022 Sep 1;8(3):e001346.

Wang P, Ma H, Zhang Y, Zeng R, Yu J, Liu R, Jin X, Zhao Y. Plasma exosome-derived microRNAs as novel biomarkers of traumatic brain injury in rats. Int J Med Sci. 2020;17(4):437.

West SW, Starling L, Kemp S, Williams S, Cross M, Taylor A, Brooks JH, Stokes KA. Trends in match injury risk in professional male rugby union: a 16-season review of 10 851 match injuries in the English Premiership (2002–2019): the Professional Rugby Injury Surveillance Project. Br J Sports Med. 2021 Jun 1;55(12):676-82.

West SW, Williams S, Kemp S, Eager R, Cross MJ, Stokes KA. Training load, injury burden, and team success in professional rugby union: Risk versus reward. J Athl Train. 2020 Sep 1;55(9):960-6.

Wilkerson GB, Grooms DR, Acocello SN. Neuromechanical considerations for post-concussion musculoskeletal injury risk management. Curr Sports Med Rep. 2017 Nov 1;16(6):419-27.

Williams JM, Langdon JL, McMillan JL, Buckley TA. English professional football players concussion knowledge and attitude. J Sport Health Sci. 2016 Jun 1;5(2):197-204.

Williams S, Robertson C, Starling L, McKay C, West S, Brown J, Stokes K. Injuries in Elite Men's Rugby Union: An Updated (2012–2020) Meta-Analysis of 11,620 Match and Training Injuries. Sports Med. 2021 Dec 2:1-4.

Williams S, Trewartha G, Kemp S, Stokes K. A meta-analysis of injuries in senior men's professional Rugby Union. Sports Med. 2013 Oct;43(10):1043-55.

Williams S, Trewartha G, Kemp S, Brooks JH, Fuller CW, Taylor AE, Cross MJ, Shaddick G, Stokes KA. How much rugby is too much? A seven-season prospective cohort study of match exposure and injury risk in professional rugby union players. Sports Med. 2017 Nov;47(11):2395-402.

Wilson R, Plumley D. Different shaped ball, same financial problems? A holistic performance assessment of English Rugby Union (2006-2015). Sport Bus Manag Int J. 2017 May 8.

Windt J, Gabbett TJ. How do training and competition workloads relate to injury? The workload—injury aetiology model. Br J Sports Med. 2017 Mar 1;51(5):428-35.

World Rugby Participation Data (accessed July 2021) https://resources.world.rugby/worldrugby/document/2020/07/28/212ed9

Yeo PC, Yeo EQ, Probert J, Sim SH, Sirisena D. A systematic review and qualitative analysis of concussion knowledge amongst sports coaches and match officials. J Sports Sci Med. 2020 Mar;19(1):65.

Yeoman B, Birch PD, Runswick OR. The effects of smart phone video analysis on focus of attention and performance in practice and competition. Psychol Sport Exerc. 2020 Mar 1;47:101644.

Yeomans C, Kenny IC, Cahalan R, Warrington GD, Harrison AJ, Hayes K, Lyons M, Campbell MJ, Comyns TM. The incidence of injury in amateur male rugby union: a systematic review and meta-analysis. Sports Med. 2018 Apr;48(4):837-48.

Yorke AM, Smith L, Babcock M, Alsalaheen B. Validity and reliability of the vestibular/ocular motor screening and associations with common concussion screening tools. Sports Health. 2017 Mar;9(2):174-80.

Yrondi A, Brauge D, LeMen J, Arbus C, Pariente J. Depression and sports-related concussion: a systematic review. Presse Med. 2017 Oct 1;46(10):890-902.

Zabaloy S, Tondelli E, Pereira LA, Freitas TT, Loturco I. Training and testing practices of strength and conditioning coaches in Argentinian Rugby Union. International Journal of Sports Science & Coaching. 2022 Dec;17(6):1331-44.

Zahid AB, Hubbard ME, Lockyer J, Podolak O, Dammavalam VM, Grady M, Nance M, Scheiman M, Samadani U, Master CL. Eye tracking as a biomarker for concussion in children. Clin J Sport Med. 2020 Sep 1;30(5):433-43.

Appendix

Qualitative Interviews Study – Interview Guide

Section A - Introduction

1. General background; name, location, brief summary of career (start to finish)

2. Sequence / details of career up to retirement per club

3. Duration of career & reasons for eventual retirement

4. What decided you to go into professional rugby / kept you involved?

5. Pros and cons of professional rugby (subjective)

6. Concussion awareness while playing/ concussion incidence while playing

7. Did concussion awareness change once retired?

8. Injuries experienced / condition of your body currently / long term effects of a professional rugby career?

9. What injuries were you most worried about sustaining as a player?

Section B - Knowledge

1. How would you describe a concussion to another person?

2. Have you experienced a concussion?* (some questions below may not be relevant if not)

3. What type of symptoms would you say are typically associated with concussions?

**state all symptoms and repeat Q 2 if needed (Rivermead Questionnaire)…Based on what we have discussed, do you now think you may have had a concussion

4. Would you or did you continue playing a sport while having a headache that resulted from a suspected concussion? Or did you see others do this?

5. Did you feel a responsibility to return to a game even if it meant playing while still experiencing symptoms of concussion? (or again refer to others they knew if not themselves)

6. Are concussions considered less important than other injuries in your opinion?

7. Do you think having one concussion means you were more likely to have another concussion?

8. Did you see instances when players clearly had a concussion on the field but were not removed from play?

9. Have you seen any one experience a concussion where there isn't a direct hit to the head?

10. How long do you think/did your symptoms of a concussion last (several weeks or gone after 10 days – prompt don't say)

11. Post-concussion; brain imaging (CAT Scan, MRI, X-Ray, etc.) typically shows visible physical damage (e.g. bruise, blood clot) to the brain.

Q – do you think brain imaging will show physical damage after a concussion?

12. Did you or a fellow player experience emotional disruptions post impact / concussion? (can personalise if necessary)

13. Personal attitude towards concussion as a player and now as a retired player?

Q – What is your personal attitude to concussion, do you think it is overhyped?

Section C - Management, treatment, support (post-concussion)

1. What was the initial on field management (i.e., identification and removal) – was it consistent across clubs?

2. Were there aligned protocols across the organisation (i.e. ,coaching, medical, S&C)?

Lines of communication with medical teams / health professionals

3. Were coaches cautious when determining whether an athlete should return to play, did coaches dictate RTP?

4. Personal experience on return to play protocols – variance between amateur and/or professional (positives & negatives)

5. Personal approach to recovery from impacts / concussion

6. Do you think there is a risk to long-term health and well-being from multiple concussions?

7. Did you experience any impediments to recovery and barriers to treatment and recovery length?

8. Did you have support from other sources (e.g., neuroscientists etc)?

9. Do you think any sport equipment e.g. mouthguards or soft-shell helmets protect the brain and/or being knocked out?

Section D – Law changes, reduce injury risk

1. What law changes do you think could be introduced to reduce injury risk and/or concussion risk (Follow on - do you think they should be?)

2. Can you suggest any changes to how the game is played to mitigate (any) injury / concussion risk?

3. Can coaches, club owners do anything to reduce injury risk or long-term effects of injury on retired players? Do you think this is their responsibility?

4. Closing comments that you'd like to include

The Rivermead Post-Concussion Symptoms Questionnaire.

0 = Not experienced at all 1 = No more of a problem 2 = A mild problem 3 = A moderate problem 4 = A severe problem Compared with before the accident, do you now (i.e., over the last 24 hours) suffer from:

Headaches.. 0 1 2 3 4

Feelings of Dizziness 0 1 2 3 4

Nausea and/or Vomiting 0 1 2 3 4

Noise Sensitivity, easily upset by loud noise 0 1 2 3 4

Sleep Disturbance 0 1 2 3 4

Fatigue, tiring more easily 0 1 2 3 4

Being Irritable, easily angered 0 1 2 3 4

Feeling Depressed or Tearful 0 1 2 3 4

Feeling Frustrated or Impatient 0 1 2 3 4

Forgetfulness, poor memory 0 1 2 3 4

Poor Concentration 0 1 2 3 4

Taking Longer to Think 0 1 2 3 4

Blurred Vision 0 1 2 3 4

Light Sensitivity, easily upset by bright light 0 1 2 3 4

Double Vision 0 1 2 3 4

Restlessness 0 1 2 3 4

Are you experiencing any other difficulties?

1. ________________________________ 0 1 2 3 4

2. ________________________________ 0 1 2 3 4

*King, N., Crawford, S., Wenden, F., Moss, N., and Wade, D. (1995) J. Neurology 242: 587-592