The Conspicuously Clandestine Epidemic: An evaluation of subconcussive head acceleration exposure in two seasons of elite men's rugby union

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The Conspicuously Clandestine Epidemic

An evaluation of subconcussive head acceleration exposure in two seasons of elite men's rugby union

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A thesis submitted in partial fulfilment for the degree of *Doctor of Philosophy*

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Declaration of Originality

I confirm that the this thesis is entirely my own work, free from copyright or plagiarism, completed under the supervision of Dr Paul Chazot (*Department of Biosciences*), Dr Louis Aslett (*Department of Mathematical Sciences*) and Dr Caroline Dodd-Reynolds (*Department of Sport and Exercise Sciences*), or formerly under the supervision of Dr Karen Hind (*Department of Sport and Exercise Sciences* - now no affiliation) and Mr Jonathan Frawley (*Advanced Research Computing* - now no affiliation). No part of this thesis has been submitted elsewhere for any degree or qualification.

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"It may take a village to raise a child, but it took three university departments to write this thesis."

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Quotes for Future PhD Candidates

"It may take a village to raise a child, but it takes an army and some to complete a PhD thesis."

- Unknown

"*Sometimes you've just got to eat that elephant one bite at a time!*"

- Desmond Tutu

"*I often quote myself. It adds spice to the conversation.*"

- George Bernard Shaw

"*The beginning of knowledge is the discovery of something we do not understand.*"

- Frank Herbert

"*Time is a great teacher. Unfortunately, it kills all its pupils*."

- Hector Louis Berlioz

"*The brain of a graduate student is like champagne. Canadian champagne.*"

- Robertson Davies

"*Sometimes a scream is better than a thesis.*"

- Ralph Waldo Emerson

"*Graduate school is the snooze button on the alarm clock of life*."

- John Rogers

Doctor (noun)

1. A person who is qualified to treat people who are ill.
2. A person who holds the highest university degree.

Origin:

Latin → Latin → Old French → Middle English

docere → *doctor* → *doctour* → *doctor*

to teach → teacher → church father → learned person

Abstract

Rugby union is one of the world's most popular team contact sports, with over 7.73 million players participating across 121 countries worldwide (Viviers et al., 2018). It is also a full-contact sport involving multiple collisions which brings an inherent risk of injury. It is estimated that elite-level rugby union players are exposed to approximately 11,000 head acceleration events across one season (Owens et al., 2021), with most injuries resulting from the main contact events including the tackle (24 - 58%), breakdown or ruck (6 - 17%), maul (12 - 16%), collisions (8 - 9%), and scrum (2 - 8%) (Fuller et al., 2007). Despite rugby union's popularity, concussion injury rates are of growing concern (Hind et al., 2020; West et al., 2021; Yeomans et al., 2018) and there are additional concerns about the cumulative effects of repeated sub-concussions, which are inherently difficult to monitor (Caplan et al., 2016). Since 2016, an increasingly common method of monitoring total and peak exposure to head acceleration has been through the use of instrumented telemetry units (ITU) in the form of external sensors or mouthguards (Wu et al., 2016b). These ITUs usually provide triaxial accelerometer and gyroscope outputs that can be converted into *g-force* and radians per second respectively. This can be used to identify which events are resulting in a high magnitude of linear or angular acceleration whilst the player is participating in their match or training session, often identifying outwardly inconsequential contact as contributing to subconcussive loading.

The primary aim of this thesis was to quantify peak linear (PLA) and peak angular (PAA) head acceleration associated with different common contact events (tackle, ruck, scrum, maul and lineout) during professional rugby union matches. In addition, this thesis looked to outline variation in the magnitude of head acceleration events where contact event role, orientation or height were changed. Player position group and player position were also

assessed to outline the varying experience of linear and angular head acceleration during contact events. Further investigation was conducted to summarise the differences in player experience of head acceleration events across two different tiers of English professional rugby union.

Seventy-one professional rugby union players, aged between 18 - 35 years old, participated in 22 matches whilst wearing an instrumented head acceleration monitoring unit (Protxx Inc., California, USA). A maximum of 23 players wore an ITU per match. The head acceleration events were reviewed using a custom-built video analysis software that allowed the “tagging” of HAEs to assign them a specific contact event type, orientation, specific player, player role, player position group, and player position. All video analysis was reviewed by a team of rugby union experts. Analysis of head acceleration events was conducted using a combination of Python Software Foundation, Python Language Reference, [Version: 3.11.]), RStudio (RStudio team, Boston, MA, USA) and SPSS 28.0 (IBM Statistics, NY, USA).

Across the two seasons, 20399 head acceleration events were collected, analysed and attributed to various contact events. The most common event was the tackle (frequency = 3774). The contact events with the highest median PLA were maul events (11.43g, IQR = 3.0), whereas median PAA was highest during tackle events (4528.46 rad/s^2, IQR = 3847.35). Orientation and player role dictated the experience of head acceleration involved in each contact event. There were limited significant differences in head acceleration magnitude discovered between contact events. However, there were several statistically significant intra-event differences between player roles of the contact events. Premiership matches tended to have a higher median PLA (11.54, IQR = 0.85) and PAA (4765.38 rad/s^2, IQR = 819.19). The Championship season had a higher per player per game contact event frequency (43.42). The player group that was exposed to the highest relative frequency of contact events was G3 (back row). G3 players were also exposed to the highest median PAA (4359.34 rad/s^2, IQR =

4523.09) during and second highest median PLA (10.93g, IQR = 2.33) during contact events. G4 players (half-backs) had the lowest relative frequency of contact events accompanied by lowest median PLA (10.71g, IQR = 1.58) and the second lowest median PAA (3659.02 rad/s^2, IQR = 3409.25). Flankers ranked highest when positions were compared using relative contact event frequency. Scrum-halves ranked last in terms of contact event frequency. Locks had the highest median PLA (10.95g, IQR = 2.45), whereas number eights had the highest median PAA (4654.94 rad/s^2, IQR = 4440.10).

To mitigate for the high cumulative subconcussive load experienced by all professional rugby union players, it is important for legislators, coaches and managers to be aware of the events, positions and player roles that result in the accumulation of subconcussive head accelerations events. In order to manage a player's exposure over a full career, it may be necessary to provide coaching interventions on contact event technique and apply limitations on playing time to adequately protect the future health of professional players.

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List of Abbreviations

ABS - Acrylonitrile Butadiene Styrene Plastic

CT - Computed Tomography Scan

DAI - Diffuse Axonal Injury

GCS - Glasgow Coma Scale

GRTP - Graduated Return to Play

HAE - Head Acceleration Event

HIA - Head Injury Assessment

iMG - Instrumented Mouthguard

ITU - Instrumented Telemetry Unit

KDT - King-Devick Test

mdTBI - Moderate Traumatic Brain Injury

MRI - Magnetic Resonance Imaging Scan

mTBI - Mild Traumatic Brain Injury

MTL - Medial Temporal Lobe

PAA - Peak Angular Acceleration

PHs - Player Hour(s)

PLA - Peak Linear Acceleration

PRISP - Professional Rugby Injury Surveillance Project

PTA - Post Traumatic Amnesia

SARIISPP - South African Rugby Injury and Illness Surveillance and Prevention Project

SCAT (-5) - Sport Concussion Assessment Tool

sTBI - Severe Traumatic Brain Injury

TBI - Traumatic Brain Injury

VCST - Visual Cognitive Screening Tool

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Chapter 1

Introduction

"I have no recollection of winning the World Cup in 2003, or of being in Australia for the tournament. Knowing what I know now, I wish that I had never turned professional."

- Steve Thompson MBE, Rugby World Cup Winner 2003. Born 1978 - Present.

1.1. Epidemiological Overview of mTBI in Rugby Union

Mild traumatic brain injury (mTBI) in sport has gained significant attention over the past decade due to the rise in neurodegenerative diseases being directly linked to participation in contact and collision sports at both elite and community levels (Shah et al., 2020). Although the majority of risk associated with brain injury in sport is allied with contact sports (Prien et al., 2018), there is growing concern that sports where there is risk of accidental collision, for example, football, basketball and field hockey could also carry a significant possibility of sustaining a brain injury. Whilst it has been suggested that non-contact and limited-contact athletes report concussion incidences more often than their contact athlete counterparts (Weber et al., 2019), it is impossible to ignore, both the academic and anecdotal evidence, for the much greater incidence of brain injury in full contact sports (Hume et al., 2017; Prien et al., 2018). Several contact sports have been shown to have a higher mTBI incidence rate that their non-contact equivalents. For elite American football, Mack et al. (2021) suggest a mTBI incidence rate of 6.61 per 1000 player hours, for elite Australian rules football, Saw et al. (2018) suggest a slightly lower mTBI incidence rate of 6 per 1000 player hours and for elite rugby league Gardner et al. (2015) suggest an incidence rate between 8.0 - 17.1 per 1000 player hours. However, elite rugby union leads the way with a mTBI incidence rate of 21.5 per 1000 player hours (Rafferty et al., 2019).

Since the instigation of professionalism in rugby union, and following the adoption of professional standards by the International Rugby Board (IRB) (now World Rugby) in 1995 (Garraway, 2000), the incidence rate of mTBI in rugby union has been steadily increasing (Rafferty et al., 2019). An early injury surveillance study conducted on a cohort of South African Super 12 clubs during the 2004-2005 season indicated a mTBI incidence rate of 1.4 per 1000 PHs (Holtzhausen et al., 2006), in contrast, a decade later, the 2014-2015 English Rugby Football Union (RFU) player injury surveillance project (PRISP) indicated an increased mTBI incidence rate of 15.8 per 1000 player hours (Rafferty et al., 2019; West et al., 2021) with the latest iteration of the PRISP reporting the further increase previously mentioned (Rafferty et al., 2019). West et al. (2021) go on to highlight that during the twenty-year period that the RFU have been conducting the PRISP, mTBI has been the most common injury, with the highest injury severity and therefore the highest injury burden, every season since 2011. In this example, and throughout the remainder of the thesis, injury severity is defined as the number of days lost from matches or training sessions as a result of an injury, a definition consistent with West et al. (2021) and Viviers et al. (2018). Further details around rugby union mTBI frequency, severity and burden are discussed in Chapter.2.

For elite rugby union, 2002 to 2010 was described as the period of mTBI stability, incidence rates varied between 5.0 per 1000 player hours and 7.2 per 1000s player hours (West et al., 2021). The period of stability was then followed by the period of growth between 2010 to 2017, where injury incidence grew to around 20.0 per 1000 player hours (Brooks and Kemp, 2008; Viviers et al., 2018). More recently, elite rugby union is observing a period of incidence re-stabilisation (2017-present). Incidence rates have been static for the past three seasons in the English premiership, and non-significant changes have been seen in other elite leagues across the world, for example, the South African Rugby Injury and Illness Surveillance and Prevention Project (SARIISPP) reported decreasing mTBI incidence rate between 2018 and

2021 (14.9 per 1000 PHs to 6.9 per 1000 PHs) (Starling et al., 2021). Outside of the PRISP and SARIISPP, there is limited surveillance data published from seasons prior to 2017, but studies conducted between 2010 and 2017 all tend to follow similar increases in incidence. Cosgrave and Williams (2019) with a cohort of professional Irish rugby union players suggested incidence rates of 18.7 per 1000 PHs across the 2016 - 2017 season and Bitchell et al. (2020) support this trend reporting increased incidence of 10.6 per 1000 player hours to 21.4 per 1000 player hours in Welsh professional rugby union players during the 2012 - 2013 and 2016 - 17 seasons, respectively.

1.2. Detection and Mitigation of mTBI in Rugby Union

As prevalence of mTBI increased, several protocol amendments, and awareness and educational programmes were introduced by World Rugby in an attempt to stem the rising incidence rates. The first protocol change was the graduated return to play protocol (GRTP) which was introduced in 2011 to ensure any players with a suspected mTBI would follow a series of guidelines to progressively return to the rugby pitch whilst ensuring they remained symptom-free (World Rugby, 2020). The GRTP consists of six stages, each separated by a minimum of 24 hours, where the player completes the end of the their recommended rest period, followed by four stages of training-based restricted activity before returning to full match play (World Rugby, 2020). In the elite game, GRTP was followed by the introduction of Head Injury Assessment (HIA), where a player could be temporarily, or permanently, removed and assessed by a medical clinician for mTBI. Head Injury Assessment has three stages. HIA1 consists of an off-field assessment with four components consisting of twelve immediate and permanent removal criteria, an off-field assessment tool (SCAT-5), pitch-side video review, and clinical evaluation. HIA2 follows for all players who enter the HIA protocol and consists of a clinical evaluation and repeat of SCAT-5 protocol no later than three hours after the match, and HIA3 is completed after thirty-six to forty-eight hours post injury where further medical assessment is completed to evaluate clinical progression of the injury (World Rugby, 2021). Several amendments have been made to the HIA, most notably since the 2016 Concussion Consensus Statement (McCrory et al., 2017), where HIA1 mandatory off-field time was increased to 12 minutes from 10 minutes and further guidance was added for conducting the HIA2 and HIA3 baseline assessments (World Rugby, 2021). Since the introduction of HIA, there has been near constant criticism of the protocol from media sources. In a news article by Fanning (2022) he suggests that HIA is not fit for purpose, concussion activists Progressive Rugby claimed that HIA was being exposed following the poor management of an international player with suspected mTBI (Morgan, 2022), and a former medical adviser to World Rugby suggested that "[HIA] was obviously [created] for commercial reasons"[1] (Cummisky, 2021). Further discussion of the merits of the current mTBI recognition and management protocols in elite rugby union can be found in Chapter.2. The use of instrumented telemetry recording devices for mTBI detection and recognition has increased substantially over the duration of thesis study period (2019 - 2024). Prior to the commencement of the study, 14 instrumented telemetry devices were presented in peer reviewed journals ranging from instrumented telemetry units to instrumented mouthguards and helmets and skullcaps. This is further discussed in Chapter 2.

To support the HIA process and to continue to raise awareness in the professional game, annual mandatory standardised mTBI education was introduced at the beginning of the 2014 - 2015 season (West et al., 2021) following the launch of HEADCASE (Rugby Football Union, 2013) to all levels of English rugby union in January 2013 (Oliver et al., 2022). HEADCASE encompasses information around mTBI recognition, some resultant conditions

[1] Cumisky (2021). The Irish Times.

that occur if the injury is poorly managed, for example, Secondary Impact Syndrome (SIS) and Chronic Traumatic Encephalopathy (CTE), in addition, to advise around prevention of the injury at common contact events and management in line with the GRTP protocol to safely return the player to the pitch. To support identification of mTBI during games, real-time video review and independent matchday doctors were added in 2016 and 2019 respectively in tier 1 and international fixtures (West et al., 2021). Although significant changes have been made by the RFU in attempts to prevent the rise of mTBI in elite rugby union, the sport has only recently entered the period of apparent injury re-stabilisation (Brooks and Kemp, 2008; Viviers et al., 2018). However, without understanding of the reasons for increasing prevalence, it could be proposed that any medical protocol, or "laws of the game" changes offer only temporary respite from further mTBI incidents.

In addition to increasing head injury incidence rate, the changes in anthropomorphic characteristics of players since 1995 has contributed to an increased overall injury incidence rate (Fuller et al., 2007). Between 1999 and 2019, player body mass, fat-free body mass and maximum sprinting velocity have all increased significantly whilst body fat percentage has decreased (Bevan et al., 2022). During the period of mTBI growth between 2010 and 2017, front-five positions mean mass increased from 115 kg to 119 kg, back row positions mean mass increased from 107 kg to 111 kg, and back-five positions mean mass increased from 93 kg to 96 kg (Bevan et al., 2022). Half-back mean mass remained relatively consistent during the growth period. The research conducted by Bevan et al. (2022) comprised of 910 seasons of data across tier one of European of professional rugby union, involving 291 players, some who had between two and five consecutive seasons of observation. Alongside an increase in mass, the increase in velocity across all player groups has subsequently led to an increase in player momentum ($p = mv$), resulting in a risk of higher momentum collisions and therefore, an increased potential for injury (Bevan et al., 2022). A more recent study (Tucker et al., 2021), indicated that the increase in player mass has now plateaued, at the time of writing, amongst international men's and women's levels, therefore suggesting that any increase in collision momentum in the immediate future will come from players becoming more conditioned to generate higher collision velocities (Bevan et al., 2022; Tucker et al., 2021).

There are several suggestions attempting to explain the increase in mTBI prevalence in elite rugby union. Shah et al. (2020) insinuates that the rise in incidence rate across the past two decades could be a reflection of the improving early detection, diagnostic abilities and more accurate reporting of mTBI. There is also the suggestion that increased rates of mTBI have been seen across society and are not just limited to sporting settings (Laker, 2011). Ultimately, the combined effect of professionalism, protocol introductions, media attention and increased education around the injury will have contributed to the reporting of mTBI events across rugby union populations.

1.3. Basic Characterisation of mTBI events in Rugby Union

During the initial period of mTBI stabilisation, the scrum and off-ball collisions have been highlighted as the highest risk, compared to tackle and ruck events, when considering the propensity for causing injury (Fuller et al., 2007) and these have therefore, dominated much of early rugby union injury literature (McIntosh, 2005; Noakes et al., 1999; Quarrie et al., 2002). Prior to 2007, scrum injury resulting in cervical spine or spinal cord damage was more probable during scrum engagement than in scrum collapse (Gianotti et al., 2008). This emphasised that, excluding catastrophic injuries during scrum collapse, legal match play resulted in a greater quantity of injuries, than events where a team was penalised (Fuller et al., 2007). Similarly, the tackle has dominated recent rugby union injury research, however, some researchers had stressed the propensity for head contact being damaging, for both tackler and ballcarrier, long before rugby union's concussion crisis began (Chalmers et al., 2004; Fuller et al. 2007; Quarrie and Hopkins, 2008). The growth of mTBI incidence and the decrease of cervical spine injury in elite rugby union has altered the focus of World Rugby and the RFU towards enforcing welfare changes in tackle laws, with the most commonly proposed solution being that of reducing tackle height (Tierney et al., 2018; Tierney and Simms, 2017; Tierney and Simms, 2018). A reduce tackle height trial was conducted in tier two of English professional rugby (Greene King IPA Championship) which aimed to reduce incidences of mTBI for both tackler and ballcarrier (Stokes et al., 2021). The prospective trial involved all 12 teams in the Championship during the 2018 - 2019 season and the lowered tackle height law was applied only in the Championship Cup fixtures, equating to 36 matches. The 90 league matches used the traditional tackle height law as outlined by World Rugby (2020). The trial reduced the frequency of mTBI for ballcarriers, however, overall mTBI tackle incidence rate did not decrease and mTBI incidence for tacklers significantly increased (Stokes et al., 2021). This implies that a reduced tackle height would be unlikely to reduce rates of mTBI if integrated across the professional game.

Notwithstanding the changes in laws and anthropomorphic characteristics of professional rugby players, there has be a consistent trend since the beginning of the professional era indicating a positive correlation between mTBI incidence rates and increasing standard of rugby (International: 180 injuries/1000 player hours, Professional Men's: 100 injuries/1000 player hours, Community Men's: 25 injuries/1000 player hours) (Viviers et al., 2018). Elite men's rugby union has the highest mTBI incidence rate, and this requires further research to understand the reasons behind this phenomenon.

In terms of characterising the expected magnitude of linear and angular head acceleration events in rugby union, linear magnitudes of 6g have been observed during roller coaster rides

(Pfister et al., 2009), 8g magnitude events have been observed during non-contact events in rugby union (Tooby et al., 2022b), and trampolining has recorded linear magnitudes of 10g (Sands et al., 2019). The lowest linear threshold of a medically determined concussion mTBI occurring across contact sports is suggested to be approximately 50g (Freeman, 2018; Gabler et al., 2020; Pellman et al., 2003). However, head acceleration events of between 10-15g have been suggested to be a more accurate predictor of chronic traumatic pathology than using mTBI medical history (Daneshvar et al., 2023). Expected head acceleration during rugby contact events has been reported to range between 10g - 164g regarding linear acceleration (King et al., 2015) with angular acceleration ranging between 3600 rad/s^2 - 6000 rad/s^2 (Roe et al., 2024).

1.4. Current State of Play: Rugby Union, mTBI and the media

The steady increase of mTBI incidences has drawn significant media scrutiny focussed on the RFU and Premiership Rugby's management of potential mTBI events. Several former elite players have joined litigation cases that have shrouded the elite game and led to the coining of the phrase 'Concussion Crisis' (Malcolm, 2021). Perhaps the most infamous of these litigation cases involves approximately 185 claimants including 2003 Rugby World Cup winner and former England international Steve Thompson and former Welsh captain Ryan Jones (The Guardian, 2022). The representative of the claimants, state the aims of the litigation are to have mTBI recognised as an industrial injury in sports and to hold sporting governing bodies accountable for negligent behaviour resulting in hundreds of ex-professional players suffering from neurological disorders (Rylands Garth PLC, 2023).

During the period of undertaking this thesis (October 2019 - October 2023), there have been several notable instances where mTBI in rugby union has drawn media attention. These have been where mTBI has been missed, mis-identified or return to play protocols have been misinterpreted. For example in November 2022, World Rugby admitted that HIA had been incorrectly applied when Australian international Nic White returned to the field after displaying clear criteria one symptoms (Rugby Pass, 2022). During the 2022 tour of Australia, England internationals Maro Itoje and 'Kamikaze Kids'[2] Sam Underhill and Tom Curry were all removed from the England squad following mTBI and contestation around the severity of their injuries (Meagher, 2022). Finally, in the opening fixture of the Lions tour to South Africa in 2021, Luke Cowan-Dickie started for the Lions after being knocked unconscious in a mistimed tackle during a Premiership fixture only 7 days prior (Heagney, 2021). With the exception of White's injury, World Rugby insisted that mTBI protocols were all correctly applied in the given examples, however, concerns similar to those raised by Morgan (2022), Fanning (2022) and Cummisky (2021) around the suitability of the protocol have been consistently reiterated across rugby media platforms. It is worth noting that none of these sources are academic, however, the media plays a vital role in highlighting areas of concern and driving changes in protocol and research direction.

The legal team for the players seeking litigation with the RFU also support the idea of subconcussion contributing to progressive neurodegeneration (Rylands Garth PLC, 2023). Subconcussion trauma occurs with the same mechanism of injury as generic mTBI, however, with none of the observable symptoms displayed (Rawlings et al., 2020). Nevertheless, the lack of observable symptoms does not denote an absence of change in neural integrity, but in fact, implies the opposite, with several studies indicating changes in neurological structure amongst contact athletes with minimal reported mTBI history (Bailes et al., 2013; Hirad et al., 2019; Nauman and Talavage, 2018). The issue with any subconcussive trauma is the

[2] Meagher (2019). The Guardian. *Eddie Jones picks 'Kamikaze Kids' Curry and Underhill to face Ireland.* Underhill (23) and Curry (21) were named the "Kamikaze Kids" by England head coach Eddie Jones for their willingness to 'tackle anything that moves' in tandem with their extensive injury histories at early stages in their careers.

difficulty in immediate, or semi-immediate, identification of the injury thus often inhibiting the removal or evaluation of players (Rawlings et al., 2020). Therefore, players may receive a multitude of subconcussive traumas whilst partaking in common rugby activities, without any knowledge of any injury occurring (Bailes et al., 2013).

1.5. Direction of Research

As outlined earlier, the traditional mTBI identification procedures often result in missed mTBI incidences or in a flexible interpretation of the GRTP due to contestation around criteria of symptoms. If the potential for non-observable characteristic changes caused by multiple subconcussive events is also considered a contributing factor to neurodegenerative disorders following a professional career, it would not be surprising if more players continue to suffer from these conditions (Stewart, 2021). It could be argued that the focal area highlighted by media coverage and academic commentary alike is the difficulty around mTBI identification. This could be considered a product of the distinct lack of injury quantification (Hoshizaki et al., 2017) and the over-reliance on visual-cognitive assessments (VCSTs) to highlight players who may have been involved in a potential mTBI events. Whether the injury is symptomatic of mTBI or has subconcussive potential, similar difficulties exist in identification of injury from contact events. In addition, the complexity of the required individualistic approach for each player and each contact event necessitates an awareness from team medical staff that cannot be attained when currently only two medical personnel require constant line-of-sight with on field ball position (Coughlan et al., 2021).

There are multiple factors that contribute to an individual’s ability to dissipate head acceleration following a collision, including preparedness or anticipation of impact, musculoskeletal strengths and weaknesses, and even individual specific vulnerabilities in different brain tissues (Clark and Guskiewicz, 2016). The unique reactions to objectively similar biomechanical head acceleration magnitudes highlight the difficulties in identifying potential mTBI events purely on observation alone (Broglio et al., 2017). It is clear that the relative contributions of linear and angular accelerations in relation to mTBI are clearly not understood (Clark and Guskiewicz, 2016). As there is no quantifiable definition in terms of acceleration magnitude, or observable changes in neural structure, of mTBI, identifying events where mTBI may be more common is challenging. However, this thesis looks to outline some parameters, in terms of acceleration magnitude involved in common contact events and highlight those players who may be at significantly increased risk of sustaining a higher cumulative head acceleration load.

1.6. Research Aims and Questions

The purpose of this thesis was to quantify the head acceleration experienced by players whilst partaking in common contact events associated with rugby union. Most notably, the tackle, ruck, scrum, maul and lineout, in addition to, other collision and non-contact events that cannot be assigned to a specific contact event category. Alongside, quantifying the head acceleration of contact events, this thesis will look to highlight differences in player positions, and player roles and orientations during contact events. This thesis contributes the quantification of head acceleration exposure in rugby union element, via head acceleration telemetry monitoring, to a wider series of research in the UK Rugby Health Project. Other elements in the UKRHP include blood biomarker analysis, VCST assessment and body composition to ensure the full profile around mTBI is fully understood.

1.6.1. Thesis Objectives:

1. Quantify the linear and angular head acceleration during major contact and collision events including: tackle, ruck, scrum, maul, and lineout.

2. Outline any variation in linear and angular head acceleration when contact event role, collision orientation or collision height (where applicable) are altered.
3. Highlight the difference in exposure to linear and angular head acceleration during tier one (Premiership) and tier two (Championship) matches.
4. Indicate any differences in linear and angular head acceleration and contact event involvement between player groups and player positions.

Chapter 2

Methodology

"Science, my boy, is made up of mistakes, but they are mistakes that it is useful to make, because they lead little by little to the truth."

- Jules Verne, French Novelist. b.1828 - d.1905.

Chapter 2 - List of Tables & Figures

2.1. Methodological Overview

There were several aims of this thesis to enhance the understanding around the subjective nature of concussion and sub-concussive injury. Due to the complexity of the injury, two 'streams' of measurement were required to comment on the associated mechanisms and symptoms; impact telemetry monitoring and visual-cognitive skills assessment. The following sections will provide rationale for why each stream is necessary to completely evaluate mTBI in rugby union.

2.1.1. Head Acceleration Telemetry Monitoring

Developing an understanding of the head acceleration magnitude involved in head injuries is essential for informing on contact events. When discussing the outcome of any injury, analysing the biomechanics that led to the injury occurring are the initial steps in managing the individual's recovery (Bahr and Krosshaug, 2005), in addition to informing on reflective protocol change and subsequently preventing future similar injury. Current understanding of impact exposure associated with different contact events, player positions, and cumulative impact load is limited. Head impact magnitude and frequency during rugby matches and training sessions has only been measured in isolated rugby populations, groups limited by sample size, or in controlled environments. These studies have allowed for basic indications of how magnitude and frequency could potentially be an indicator of mTBI, however, without monitoring 'live' matches, the majority of studies are yet to highlight the true magnitudes associated with contact events in rugby union (Tooby et al., 2022a). A comprehensive prospective study over multiple seasons monitoring impact exposure during 'live' matches would allow for a more representative indication (Guskiewicz and Mihalik, 2011).

Table.2.1. *Studies completed between 2012 - 2022 using impact telemetry as main data stream for assessing contact events in rugby union.* (Search criteria: “rugby”, “impact”, “telemetry”, “concussion”, “head”, “injury”, “devices”, “sensors”). The first 100 results were filtered by year and assessed to see if head impact telemetry was used as a main data stream. Studies were also assessed to ensure at least one rugby participant group was included.

Author	**Year**	**Title**	**ITD Type**
Gabbett	2013	*Quantifying the physical demands of collision sports: does microsensor technology measure what it claims to measure?*	GPS
Hasagawa et al.	2014	*Does clenching reduce indirect head acceleration during rugby contact?*	IMG
King et al.	2015	*Instrumented mouthguard acceleration analyses for head impacts in amateur rugby union players over a season of matches*	IMG
King et al.	2016	*Similar head impact acceleration measured using instrumented ear patches in a junior rugby union team during matches in comparison with other sports*	Skin Patch
Stephen	2016	*Investigating history of concussion and data from head impact telemetry (xPatch) in relation to neuropsychological outcomes in a sample of adult rugby players in Cape Town*	Skin Patch
King et al.	2016	*The influence of head impact threshold for reporting data in contact and collision sports: systematic review and original data analysis*	Multiple
Williams et al.	2016	*Head impact measurement devices: a clinical review*	Multiple
King et al.	2017	*Head impacts in a junior rugby league team measured with a wireless head impact sensor: an exploratory analysis*	Skin Patch
King et al.	2017	*Measurement of head impacts in a senior amateur rugby league team with an instrumented patch:*	Skin Patch

		exploratory analysis	
King et al.	2018	*Head impact exposure from match participation in women's rugby league over one season of domestic competition*	Skin Patch
King	2018	*Head impact biomechanics: Comparison between sports and genders*	Skin Patch
Miller et al.	2018	*Validation of a custom instrumented retainer form factor for measuring linear and angular head impact kinematics*	IMG*
King et al.	2019	*Head impact exposure comparison between male and female amateur rugby league participants measured with an instrumented patch*	Skin Patch
Carey et al.	2019	*Verifying head impacts recorded by a wearable sensor using video footage in rugby league: a preliminary study*	Skin Patch
Nguyen et al.	2019	*Frequency and magnitude of game-related head impacts in male contact sports athletes: a systematic review and meta-analysis*	Multiple
Tiernan et al.	2019	*Evaluation of skin-mounted sensor for head impact measurement*	Skin Patch
Tiernan et al.	2019	*The effect of impact location on brain strain*	Skin Patch
Greybe et al.	2020	*Comparison of head impact measurements via an instrumented mouthguard and an anthropometric testing device*	IMG
Stitt	2020	*Assessing technology for detection, mitigation, and simulation of concussive rugby impacts.*	Skull Cap
Kieffer et al.	2020	*A two-phased approach to quantifying head impact sensor accuracy: in-laboratory and on-field assessments*	Multiple
Patton et al.	2020	*Head impact sensor studies in sports: a systematic review of exposure confirmation methods*	Multiple
Williams et al.	2021	*Sex differences in neck strength and head injury kinematics in university rugby union players*	IMG

Marshall	2021	*An Investigation of Transmission Range for an Instrumented Mouthguard Head Impact Telemetry System for Rugby Union*	IMG
Petrie	2021	*Analysis of Head Acceleration Kinematics in Collegiate and Elite Women's Rugby Union*	IMG
Pennington	2022	*Head Acceleration in Men's University Rugby Union and the Effect of Neck Strength Training*	IMG
Hayden	2022	*Neck Strength and Head Acceleration Events in University Women's Rugby Union*	IMG
Tierney	2022	*Concussion biomechanics, head acceleration exposure and brain injury criteria in sport: a review*	IMG
Cheng et al.	2022	*Impact and workload are dominating on-field data monitoring techniques to track health and well-being of team-sports athletes*	IMG

Instrumented telemetry units (ITUs) have been used in multiple rugby studies over the past decade (Table.2.1). King and his associates have been the world leaders in rugby league research using external telemetry devices particularly between 2016 to 2018. During the purchase period for acquiring ITUs for this thesis, skin patch and skin mounted ITUs dominated the research field, with the X2 Biosystems skin patch often selected as the device of choice (King et al., 2017). More recently, IMGs have become more popular, however, no validation studies of IMGs had been completed at the time of ITU purchase. Between 2009 to 2015, almost all the ITUs manufactured were for helmeted sports. Therefore, the majority of research preceding 2012, concerning impact telemetry and contact events, was dominated by American football and ice hockey. The ITUs were purchased in 2018 for study commencement in 2019, and since late 2019, the ITU market has grown significantly and as of May 2022, there are 16 research-validated IMGs, which are now considered the 'gold-standard' of wearable ITU for rugby research.

The ITU selected for this thesis was the Protxx skin mounted telemetry device. At the time of purchase, Protxx Inc. was a relatively recently incorporated company and the ITUs were comparatively new considering usual hardware development time parameters. This rapid development was possible due to the CEO, CTO and chief technical engineer who worked to design and manufacture the X2 Biosystems skin patch, which featured in a significant proportion of research between 2012 - 2018. Published work from Protxx indicates that the phybrata (physiological vibration acceleration) IMU was a novel way for precision health monitoring (Grafton et al., 2019) and had clear indications in several validation studies that suggested that a confirmed mTBI event could be detected amongst individuals suffering from fatigue or other conditions that may impair balance (Grafton et al., 2019; Ralston et al., 2020). Further research goes on to suggest the link between the phybrata data produced by the Protxx IMU had the ability to align with diagnosed cases of mTBI (Ralston et al., 2020).

The rate at which the Protxx IMU accurately predicted which individuals had a diagnosed mTBI was reported to be over 90% in terms of sensitivity and specificity (Ralston et al., 2020). Further use of the Protxx IMU has seen it used in combination with a machine learning tool developed to use the phybrata data as a predictor of mTBI severity attempting binary classification of mTBI patients and multiclass neurophysiological impairments (Hope et al., 2021). The Protxx IMU was similarly used in an adjacent studies conducting up-and-go tests in assessment of activities of daily living (Wu et al., 2016) with IMU positioned on the sternum and the right mastoid process (Abdollah et al., 2021). The accuracy, specificity and sensitivity when the IMU was positioned on the sternum were report as 93% - 100%, 90% - 100%, and 96% - 100% respectively on the various movement tests. The accuracy, specificity and sensitivity when the IMU was positioned on the mastoid process were report as 95% - 100%, 90% - 100%, and 100% respectively. This particular study used a sample of 787 separate postural transitions and movements (Abdollah et al., 2021).

To effectively assess head acceleration telemetry, the ITU requires the ability to record linear and angular accelerations without losing the sensitivity resulting in the omission of events at a potentially subconcussive magnitude. The Protxx ITU was designed to detect accelerations at a subconcussive magnitude and therefore the linear acceleration recording cap was limited to 27.78g and angular acceleration was limited to 36404.16rad/s^2. The limitation of peak linear and angular acceleration measuring capacity was seen as acceptable. This was due to the aims of this thesis relating to the identification of subconcussive events which are traditionally of a lower magnitude than the manufacturer set limits. Most contact events in rugby union occur below the manufacturer set limits.

The ITUs contained triaxial accelerometers and gyroscopes with sampling rates of 200Hz which is considered as the minimal requirement to assess brain strain and capture impact response relevant to head injury (Wu et al., 2016a). The accelerometer and gyroscope were packaged in an ABS plastic shell, the material designed to prevent damage or deformation of the components of the ITU (Anderson et al., 2020). The data produced by the ITUs was collected from an iPad application and uploaded to an online reporting software tool provided by Protxx. In further support of the necessity of impact telemetry monitoring in rugby, the RFU have agreed to provide every team in the Gallagher Premiership, the Allianz Premier 15s, and the England international teams (men's and women's) with IMGs for the 2022/23 season.

2.2. Study Design

A prospective study design was used to best answer the research aims of this thesis whilst limiting disruption and interference with the participant group. A prospective study design was most appropriate because it provided the most complete and continuous overview of impact load and potential concussive events across multiple seasons. The research took place during the 2019/2020 season of the Greene King IPA Championship and the 2020/2021 season of the Gallagher Premiership – the two highest tiers of English professional rugby union. The first data collection date was 16th September 2019. The final data collection date was the 7th June 2021 with the main group of participants. Further data collection took place on 7th June 2021 for a sub-study participant group of this thesis (Chapter 3).

2.2.1. Ethical Approval

Prior to participant recruitment, ethical approval was provided by Durham University Research and Ethics committee. All participants were provided with an overview of the study and were fully informed on the requirements of their involvement had they agreed to participate. Participants were required to read an information sheet and complete a consent form which were stored in accordance with DSES guidelines. Participants were also provided with information on data management (Appendix D) and personal detail privacy (Appendix C & Appendix E). A risk assessment was also completed (Appendix F).

A secondary ethics application was completed before the second season of data collection began. The purpose of the secondary application was to re-establish ethical approval following protocol adaptations required due to the COVID-19 pandemic. The additions included a COVID-19 specific risk assessment and COVID-19 change of protocol document (Appendix F). Participants were required to resign their consent forms to indicate continued participation during the COVID-19 pandemic. A separate ethical application was completed for the method study (Chapter.4.) with similar documentation produced (Appendix G, Appendix H & Appendix I).

2.2.2. Participant Recruitment and Eligibility

Participants were recruited for this series of studies via a newly established relationship between Durham University Sport and Exercise Sciences department and a professional rugby union club. Permission to access players was provided by gatekeepers from the rugby union club. All players in the first team squad and senior academy squad were invited to participate. The first team and senior academy squads comprised of professional male rugby union players aged between 18 - 35 years. No exclusions were made based on ethnicity, time as a professional rugby player, time at the rugby club or injury history. Players were not asked to provide any details on concussion history. During the research, players left the club for a variety of professional and personal reasons. Any player that left the club during the research automatically opted out of any further assessment. All data contributed by players that left the club was still included in the analysis up to their point of departure.

2.3. Methods

The data collection processes for the studies that comprise this thesis are outlined in this section. Seventy-one players were involved in the study in either one or both seasons. Contact event telemetry monitoring resulted in thirty-six recording sessions spread over two seasons of the top two tiers of English men's rugby union. All data collection took place at the rugby club between September 2019 and June 2021. Fig. 2.1. outlines the general overview of the study and the timeline of data collection and analysis including where data from parts of the study are discussed in this thesis.

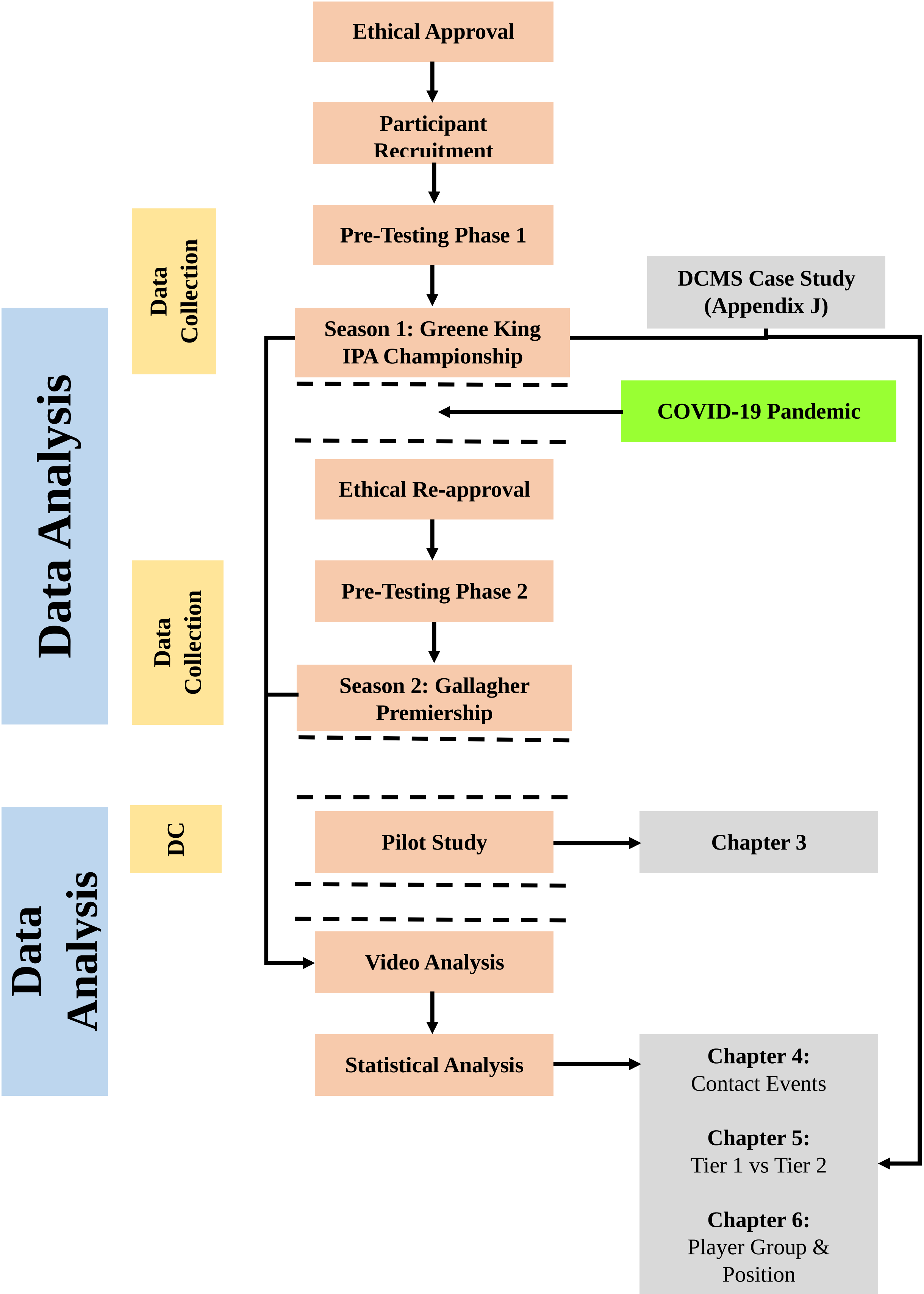

Figure 2.1. *An overview of the timeline of data collection and analysis involved in the study.*

Pre-Testing Phase (Both seasons)

The pre-testing phase involved collection of baseline data and familiarisation with the ITUs amongst players and backroom staff. Introductions to the ITUs and the outputs were conducted by the lead researcher and his primary supervisor to ensure players were familiar with the technology and understood the purpose of the research.

Season 1: Greene King IPA Championship & RFU Championship Cup (2019-2020)

During the first season of data collection, head acceleration telemetry data was collected at every home fixture between September 2019 and March 2020 until the season was postponed, and ultimately unfinished due to the start of the COVID-19 pandemic. In total, 11 matches were recorded including one preseason, 8 league and 3 cup games. A maximum of twenty-three players wore ITUs during matches due to the limitations in match-day squad size.

Season 2: Gallagher Premiership & European Rugby Challenge Cup (2020-2021)

Collection of head acceleration data continued in the second year of the study with a further 11 home matches recorded. Necessary protocol adjustments were made to mitigate for COVID-19 to protect players and researchers (Chapter.3.4.). Fewer matches were recorded than expected due to three fixtures being cancelled because of COVID-19 outbreaks in opposition teams. In addition, there were no Gallagher Premiership Cup fixtures due to concerns around maintaining the requisite number of players available to play in league fixtures. Compared to the 2022-2023 Gallagher Premiership season, the first full season since the COVID-19 pandemic, the 2020-2021 premiership season saw a forty-two percent reduction in potential fixtures[3].

[3] Potential fixtures denotes the maximum number of fixtures a team would play if they reach the final in all three competitions: Gallagher Premiership (league), Gallagher Premiership Cup, and European Challenge Cup.

Pilot Study

A pilot study took place on the 7th June 2021 involving four former professional and semi-professional rugby union players. The players completed simulated contact events including different types of tackles and rucks. A total of 198 contact events were recorded. The original purpose of the pilot study was to identify contact events by their impact telemetry outputs which could subsequently be used to train a machine learning tool. The tool could then discern positive head impact events from false positives and signal noise. Due to several participants returning positive COVID-19 lateral flow tests on the day before data collection began, the sample size of participants and therefore number of contact events became too small to effectively distinguish true events from false positives. The study did, however, provide the basis for characterisation of contact events required for the video analysis completed on the main study data set. A comprehensive description of the method study is included in Chapter.4.

2.3.1. Acceleration Telemetry Monitoring Protocol

The ITUs selected for this study were supplied by Protxx Inc. (California, USA) and provided by Department of Sport and Exercise Sciences. The product package purchased from Protxx Inc. included: twenty-four pre-assigned units, a charging and transportation case, adhesive patches, a recording application (available on any tablet), and access to an online, purpose-built recording tool. Protxx staff also provided a brief education seminar on 'best-practice' and an instruction manual defining operation parameters of the ITUs. Tablets (Apple iPad 6th Generation) to run the recording application that linked directly to the ITUs were provided by the DSES. In the event of a catastrophic failure of either ITU hardware or recording application, Protxx provided replacement hardware and regular updates to recording software. Over the duration of the study, the ITU failure rate was 2.3% with twenty-one ITUs requiring replacement[4]. The main reason for ITU failure was the adhesive binding the two hemispheres of the external shell dissolving due to excessive exposure to sweat and cleaning products. Failed ITUs were replaced with new hardware and remotely reassigned to mirror the original ITU.

Operational Protocol

ITU operation began by removing the individual ITUs from the transportation and charging case and applying them to the adhesive strips, on a plastic backing, in a patchwork pattern. The patchwork pattern allowed for easier removal of individual ITUs once applied to the adhesive strips. With sensors on adhesive strips, the recording session was started from the recording application on the iPads. The iPads connected to the ITUs via Bluetooth connections so serially engaged each ITU due to iPad Bluetooth connective capacity being limited to four connections at one time (Rüst et al., 2014). For a recording session where all twenty-four ITUs were in operation, two iPads were required to manage twelve ITUs each - a method designed to limit recording application crashes. Each iPad logged into a different 'team' of twelve ITUs (Team 1: ITU 01 - 12, Team 2: ITU 13 - 24). After initiation, the ITUs did not have to stay in Bluetooth range of the iPads. The recording session was run in local mode during all recording sessions due to risk of unstable internet connection disrupting data collection.

Due to logistical constraints on match days, recording sessions were started between 90 minutes to two hours before kick-off and ended 90 minutes to two hours after the final whistle. During all ITU data collection, start and end time of recording sessions, training

[4] This is excluding one recording session where an iPad provided by DSES froze and the recording of twelve ITDs was lost. After this incident, Protxx provided two Apple iPad 5th Generation that had fewer bugs in the recording software.

sessions, and matches was independently recorded to allow for data cleansing during analysis, including the cutting of excess recorded input prior and after targeted recording period. Sensor connectivity was checked with a visual assessment of live LED[5] and a false start protocol. The false start protocol enabled the researcher to verify the ITUs were recording and uploading to the online reporting tool. The protocol involved activating all the ITUs, creating some false events by moving the ITUs, and then uploading the false data to the online reporting tool. If all stages of the false start protocol were complete, the ITUs were deemed ready for player application.

The players were sprayed with a ‘pre-tape’ adhesive spray (Mueller Tuffner Sports Medicine Corp., WI, USA), the ITU-adhesive strip was then removed from the plastic backing and applied to the player. ITU position was on the anatomical right of the head[6], 1cm below the protruding mastoid process. The ITU was then held firmly in position for five seconds to ensure firm bonding to the skin. A further visual assessment of live LED was made by the researcher before adhesive tape (Hypafix, Smith & Nephew Healthcare Ltd, Watford, Hertfordshire, UK) was applied. The tape was cut into 5cm x 5cm squares to ensure the ITU was covered with space for approximately 1cm of tape - skin contact around the ITU site (Figure 2.2.). This process was repeated for each player partaking in the recording session.

[5] Protxx ITUs produce a red light from an LED when the accelerometer or gyroscope are activated. Therefore, if the sensor is live, motion applied, and the sensor is fully functional, the LED will display a red light.

[6] In certain cases, players preferred to wear the ITU on the left side of the head due to their playing characteristics - a blindside flanker rubs the right-side of their head in a scrum but not the left, therefore it was more comfortable for them to wear the ITU on the left. In every case where this occurred, ITU alternate position was recorded.

Figure 2.2. *ITU positioning with & without adhesive tape.*

During the recording session, the iPads were stored in a secure office to ensure cold weather or tampering did not disrupt data collection. Total recording session length was approximately five hours for both training days and matches, when including the logistically lengthy periods of non-activity. A basic ethnographic report was written during each recording session focussing on reference elements for later analysis (Table 2.2.)

Table 2.2. *Events during recording sessions where the time of the event was noted due to it being potentially essential to data cleansing or analysis.*

Notable Events
Breaks in play
Contact events with head injury potential (researcher visual assessment)
Major contact activities (training sessions)
Player substitutions
Players removed for HIA (Fail)
Players removed for HIA (Rugby Pass)

The end time of the training session or match was noted and ITUs were removed from players by players themselves, athletic support staff, and the researcher. Once all of one ‘team’ of ITUs had been collected, the iPad assigned to those twelve ITUs could end the session. The recording application downloaded data from four ITUs at a time and once all twelve ITU downloads had been completed the application could be closed. ITUs were then removed from their adhesive strips and any remaining adhesive tape before being visually inspected for damage, cleaned, and returned to the charging case. Data from the recording session was uploaded to the online reporting tool at the earliest opportunity where a stable internet connection could be guaranteed.

The data accessible on the reporting tool was threefold. The primary data set applicable to this study was the raw data recordings, in comma-separated value (csv) files. The csv files contained the triaxial data from accelerometers and gyroscopes, with associated UNIX time for each event, and a timestamp from when the recording of that team of ITUs ended. The second data set summarised the accelerometer and gyroscope data into 'average' and 'peak' measured in kWh. This data set was not used in this thesis because of the ambiguity surrounding it, but it did allow for semi-immediate feedback to club to advocate for the use of head impact monitoring in future seasons. The final data set was an indication of which ITUs had exceeded the pre-set threshold for suggested head injury assessment. This data was also not used in this thesis because Protxx Inc. were unable or unwilling to provide the threshold magnitudes.

2.3.2. Video Analysis Protocol

To identify contact events from the impact telemetry data, and to aid the identification of false positive events, a comprehensive video analysis was conducted. A purpose built 'tagging tool', constructed in HTML format, was designed which allowed the viewing of three video angles and linked directly to the raw impact csv files. The video angles were (1) a zoomed 'action focussed' angle, (2) a moving wide full pitch angle, and (3) a miscellaneous angle. The miscellaneous angle varied between a static wide-angle provided by the rugby club or where possible, the recording of the original TV broadcast. Before using the tagging tool, the raw csv files were combined into a single csv for each recording session and a list of potential contact events was constructed (Table 2.3., 2.4., 2.5. & 2.6.).

Table 2.3. *Micro, nano and pico classification of tackle types used by reviewers to tag contact events.*

Micro classification (Role)	Nano classification (Orientation)	Pico classification (Contact Height)
Ballcarrier	Front	Head Shoulder Chest Rib Hip Thigh Knee Ankle
Tackler		Head → Ankle
Ballcarrier	Side	Head → Ankle
Tackler		
Ballcarrier	Behind	Head → Ankle
Tackler		
Ballcarrier	Double	Head → Ankle
Tackler		

†*All tackle types used pico classification from head down to ankle using the eight notable locations outlined in the first row of Table 2.3. The term "Head → Ankle" replaces the list of the eight notable locations.*

Table 2.4. *Micro and nano classification of ruck types used by reviewers to tag contact events.*

Micro classification (Type)	Nano classification (Role)
Clear Out	Attacker Defender Guard Floor
Counter-ruck	Attacker, Defender, Guard, Floor
Counter-ruck from distance	Attacker, Defender, Guard, Floor
Jackal	Attacker, Defender, Guard, Floor

Table 2.5. *Micro and nano classification of scrum, lineout and maul types used by reviewers to tag contact events.*

Classification (Type)	Micro classification (Attack/Defend)	Nano classification (Role)
Scrum	Attacking	1st Row
		2nd Row
		3rd Row
	Defending	1st - 3rd Rows
Maul	Attacking	Ballcarrier
		Support Player
	Defending	Ballcarrier, Support Player
Lineout	Attacking	Jumper
		Lifter
		Support
	Defending	Jumper, Lifter, Support

Table 2.6. *Classification of non-contact and unspecified contact events.*

Classification (Type)	Micro classification
Collision	Player - Player (Non-tackle) Player - Ground (Falls)
Run	Quarter 1 Quarter 2 Quarter 3 Quarter 4

Each recording session was tagged by the researcher and then an independent research assistant completed a blind re-tag of all recording sessions as a secondary stage of verification. If there were inconsistencies between primary and secondary tagging of contact events, then the debated events were reviewed by a tertiary research assistant. The outcome of the video analysis process provided impact telemetry data assigned to a specific contact event ready for statistical analysis. At this stage, the data was anonymised, identifiable features removed, and any further reference was made via the use of player codes.

2.3.3. Statistical Analysis

Statistical analysis was completed using a combination of Python programming language (Python Software Foundation, Python Language Reference, [Version: 3.11.]), RStudio (RStudio team, Boston, MA, USA) and SPSS 28.0 (IBM Statistics, NY, USA). Graphical representations were created using Matplotlib, SPSS 28.0 and RStudio.

Descriptive statistical analysis including measures of central tendencies, dispersion and variance of tagged impact telemetry data was completed to indicate contact event frequency and head acceleration magnitude. To greater understand the ITU data produced by the individual and positional profiling, comparison of means assessments were used. Data was assessed for normality initially using Q-Q plots and histograms, however, Kolmogorov-Smirnov and Shapiro-Wilk tests were used to confirm initial normality assumptions. Following Kolmogorov-Smirnov and Shapiro-Wilk tests, positional group impact frequency and load was compared using One-way ANOVA or, the non-parametric equivalent Kruskal-Wallis H test. Individual profiles were compared using a combination of independent *t*-tests, One-way ANOVAs and where appropriate, their non-parametric equivalents; Mann-Whitney U and Kruskal-Wallis H. For the One-way ANOVA and Kruskal-Wallis H tests, a Bonferroni adjustment in the post-hoc analysis was used to mitigate for the multiple comparisons problem. The Bonferroni adjustment was appropriate for ANOVA between the player position groups due to the limited number of groups, however, Roger's method was used as the post-hoc analysis when comparing individual players due to it having the highest level of statistical power and most commonly indicating true difference between groups (Williams et al., 1992). For all statistical tests, a confidence interval of 95% was established, alongside an α value of 0.05 to indicate statistical significance. Several visualisations were used to outline trends in the data including line and scatter plots to indicate change in impact magnitude and frequency across seasons by players and player positions. Scatter plots were also used to indicate trend changes in player exposure to impact magnitude across seasons. Box plots were used to indicate variance and range in magnitude during contact events, in addition to, match, training and seasonal impact load by player position.

2.4. *SARS-CoV-2* (COVID-19) Data Collection Protocol Amendments

The first case of novel *SARS-CoV-2* in the United Kingdom was identified January 29th, 2020, followed by a rapid increase in cases until 23rd March 2020 when the first nationwide lockdown began (Moss et al., 2020). The first lockdown prematurely ended the first data collection season and the following disruption because of the pandemic, required adaptation to the research protocol for the subsequent season. The changes made to mitigate the growing health concerns and ensure safety of players and researchers are highlighted in Table 2.7.

Table 2.7. *Protocol amendments due to COVID-19 pandemic*.

Protocol Amendment	*Description*	*Date of Change*
Championship data collection postponed	*Collection of all data was immediately postponed following suspension of rugby activities by the RFU.*	14/03/20
ITU application completed by backroom staff	*In line with the government's policy on social bubbles limiting mixing with multiple groups of people, it was necessary to limit researcher-player mixing. Therefore, two members of backroom staff were trained in ITU application and completed the application for the duration of 2020-2021 season.*	01/09/20

Chapter 3

Pilot Study

'If we knew what we were doing, it would not be called research, would it?'

- Albert Einstein. Theoretical Physicist. ETH Zurich & University of Zurich. b.1879 - d.1955.

Chapter 3 - List of Tables and Figures

3.1. Introduction

Rugby union is one of the world's most popular team contact sports, with over 7.73 million players participating across 121 countries worldwide (Viviers et al., 2018). It is also a full-contact sport involving multiple collisions which brings an inherent risk of injury. It is estimated that elite-level rugby union players are exposed to approximately 11,000 impact events across one season (Owens et al., 2021), with most injuries resulting from the main contact events including the tackle (24 - 58%), breakdown or ruck (6 - 17%), maul (12 - 16%), collisions (8 - 9%), and scrum (2 - 8%) (Fuller et al., 2007). Despite rugby union's popularity, concussion injury rates are of growing concern (Hind et al., 2020; West et al., 2021; Yeomans et al., 2018) and there are additional concerns about the cumulative effects of repeated sub-concussions, which are inherently difficult to monitor (Caplan et al., 2016).

Both mTBI and sub-concussive impacts are caused by exposure to biomechanical head acceleration in linear and angular planes of motion (Tiernan et al., 2020). A mTBI caused by linear forces is suggested to result in a transient intercranial pressure gradient whereas a mTBI with a majority angular force exposure is suggested to result in a strain response (Duma and Rowson, 2013). Although exposure to both mechanisms can cause a mTBI, there is some debate as to which mechanism results in the more severe symptoms (King et al., 2003; Tiernan et al., 2020).

In terms of the contribution of angular mechanism, exposure to high angular acceleration has been attributed to great neurone strain and increased potential for axotomy (Greenwood, 2002; Maxwell, 2014). The structure of an axon makes it uniquely vulnerable when exposed to mechanical damage, due to its length and distance from the cell body (Fawcett et al., 2001). Any lesion on the axon body will result in separation from the cell body and immediate diminished availability of proteins required for homeostasis and other functions. Following trauma to the axon, the axonal cytoskeleton begins to degenerate over several days with the speed of degeneration determined by the type of axon damaged and the distance the lesion is from the cell body (Greer et al., 2013). After approximately twenty-four hours post injury, transcription factors c-jun, jun D and Krox-24 are upregulated at axotomized neurons (Fawcett et al., 2001). In neurons where the lesion site is in close proximity to the cell body, therefore making total cell death inevitable, there is increased concentrations of c-fos. Increased c-fos binds to c-jun to form transcription factor AP-1 which results in semi-immediate regulation of gene expression for cytokine production, growth factors and apoptosis (Diaz-Cañestro et al., 2019). Increased concentrations of the transcription factors can be expressed in the blood for several months post injury (Pennypacker et al., 2000). The location of the lesion on the neuron is also important for the expression of growth factor associated proteins, for example, GAP-43. GAP-43 is present on all growth cones at sites of axon growth or regeneration. High concentrations of GAP-43 are present in all damaged neurons of the PNS but are only present in CNS neurons when the lesion is close to the cell body (Fawcett et al., 2001) and therefore could be an indicator of more severe traumatic brain injury.

Necrosis, following linear mechanical insult, is always considered an abnormal and uncontrolled event. It leads to the swelling and disruption of nuclear membrane, endoplasmic reticular and cell membrane. Necrosis is usually caused by mechanical insult, but it can also be a product of anoxia caused by an insulted region of the brain becoming ischaemic. The combination of ischaemia and cellular necrosis prevent membrane ion pump functionality, unmanageable cell swelling and membrane disruption (Greif and Eichmann, 2014). Ischaemia prevents the transfer of ATP to ion pumps that require energy for direct function, most notably, the sodium-potassium pump and the calcium-hydrogen pump, responsible for maintaining potential gradients across the cell membrane (Fawcett et al., 2001). In regions without membrane pump facility, the cells swell rapidly, and necrosis occurs. In regions where the ischaemia is only partial, reduced membrane pump functionality induces the influx of calcium and sodium ions, and fluid, further lowering the membrane potential of the cells. It is the disruption to pump function and subsequent rise in intracellular calcium ions that causes much of the necrosis that occurs following mechanical insult

(Akamatsu and Hanafy, 2020). A significant increase in intracellular calcium ions is required to cause necrosis otherwise, apoptosis is more common.

Ischaemia also causes an increase in glutamate concentration in trauma areas. Glutamate increases the permeability of NMDA (N-methyl-D-aspartate) and AMPA (α-amino-3-hydroxy-5-methyl-4-isoxazolepropionic acid) channels which results in rapid increase of calcium ion diffusion into the cell (Akamatsu and Hanafy, 2020). The increase in calcium activates multiple enzymes including endonucleases, lipases, proteases and other assorted degradative enzymes that can catalyse the organelles of the cell (Weber, 2012).

Other contributors to necrosis include the increase of free radicals within in the cell due to mitochondria damage (Fawcett et al., 2001). Mitochondria can aid the buffering process of the intracellular calcium by supporting the diffusion of calcium ions into the mitochondrial matrix via membrane ATPase, therefore, preventing immediate cell necrosis (Weber, 2012). However, the increase in intramitochondrial calcium inhibits oxidative phosphorylation, increasing the presence of nitric oxide, leading to massive secretion of free radicals. The influx of calcium ions also increases the permeability of non-specific transition pores facilitating further loss of mitochondria membrane potential, causing increased swelling and dysfunction. If large concentrations of free radicals are combined with nitric oxide to produce the toxic peroxynitrite radical, severe damage will occur to multiple cell structures. The combination of these factors accelerate cellular necrosis are often enough to overwhelm glial cells causing further cascade necrosis across related cellular pathways (Fawcett et al., 2001). The presence of free radicals has also been linked to evidence of neurodegeneration (Beal, 1996).

Head acceleration telemetry units (ITUs) are used in research settings to improve understanding of head impacts during contact sports and their outcomes. In applied settings, the technology is increasingly being used to monitor player head acceleration and inform decisions on training and recovery. Various versions of sensors currently exist with those applicable to rugby falling into one of three categories; instrumented mouthguard (iMGs), soft tissue mounted (skin-patch) or headgear mounted (on a scrum/skull cap) (Wu et al., 2016). To accurately assess mTBI and subconcussion in rugby union, it is also necessary for ITUs to report both linear and angular acceleration (Duma and Rowson, 2013).

In studies to date, there has been limited effort to distinguish 'true' head acceleration from general signal noise, for example, head shaking, running and changes of direction (Cortes et al., 2017; Tiernan et al., 2019). There have also been limited attempts to gather datasets large enough to reliably distinguish contact events. Prior to completing assessment of the main dataset of head acceleration telemetry data from the professional rugby union matches (Chapter 4, Chapter 5 and Chapter 6), this pilot study was conducted to ensure protocol, methodological and data analysis rigidity. The aim of the pilot study was to outline particular contact events, and variation of different contact events that may be the focal point for future research. The study would also provide researchers with the opportunity to highlight event roles, collision orientations, or collision heights that may require further investigation with a large sample of data. In addition, this study would attempt to characterise, in terms of head acceleration, the difference between tackles and rucks.

3.2. Pilot Study Protocol

This study was a rugby union impact scenario-based, controlled observation trial. Ethical approval for the study was granted by the Department of Sport and Exercise Sciences Ethics Sub-Committee at Durham University. Four experienced and currently competitive male rugby union players ($Median_{Age}$ = 26 y, $Median_{Height}$ = 182.5 cm, $Median_{Mass}$ = 94 kg) provided informed consent and agreed to take part in the study.

Head Impact Telemetry System

Protxx skin-mounted sensor units (ITU) (Protxx Inc. California, USA) were used to detect and quantify head acceleration events. The ITUs contain both triaxial accelerometers and triaxial gyroscopes to record linear and angular head acceleration. The units were positioned 5mm below the right and the left mastoid process (Chapter 2) (King et al., 2016; King et al., 2017) and attached using adhesive strips (Protxx Inc., California, USA), adhesive spray (Mueller Tuffner Sports Medicine Corp., WI, USA), and then covered with adhesive tape (Smith & Nephew Healthcare Ltd, Watford, Hertfordshire, UK) to prevent movement.

There were four distinct phases, each designed to focus on a specific rugby union event: non-contact events (running), tackles (one tackler and one ballcarrier), rucks (up to three attacking or defending players total), and double tackles (two tacklers and one ballcarrier). The timings of each phase and scenario were recorded to ensure the correct labelling of impact events for data analysis. Phase one was a warm-up including running at different velocities, changes of direction, and preparation for contact drills to ensure safety of participants. Phase two included a series of one-on-one tackle scenarios at different heights and orientations. Side tackles were completed above (SAW) and below (SBW) the ballcarrier's waist. Front (FBW) and behind (BHBW) tackles were only completed below the ballcarrier's waist. Four of each tackle scenario were completed with each player completing tackles as both the tackler and the ballcarrier. Players were informed of the type of tackle to make prior to the beginning of each scenario. All tackles completed were legal rugby union tackles as defined by World Rugby (World Rugby, 2021) with no direct contact to the head of ball-carrier or tackler during any of the scenarios.

Phase three consisted of different ruck scenarios. However, to simulate live play and breakdown mechanics, players were instructed to compete at the ruck without being preassigned a particular technique. Two players started each scenario in a prone position facing each other, either side of a third player acting as the tackled ballcarrier. On the whistle, players then retreated to a cone, one metre away for the attacking player, and two or three metres away for the defending player. Players were then allowed to compete using any techniques considered legal in rugby union as defined by World Rugby (World Rugby, 2021). Six scenarios were completed with ruck types and techniques verified after the scenario had been completed by a rugby coach.

Table 3.1. *Types and descriptions of breakdowns identified in live scenarios.*

Type	**Observations**
Jackal (JCK)	Players arrive at the ruck at approximately the same time with defender attempting to gain possession of the ball with hands before the ruck is formed. Low velocity of collision and long duration of contact event.
Clearout (CO)	Defender arrives at ruck shortly before attacker with the attacker winning the competition and removing the defender from the ruck. Medium collision velocity and medium duration of contact event.
Counter Ruck (CR)	Attacker arrives at the ruck shortly before defender with the defender winning the ruck by driving the attacker off the ball. Medium collision velocity and medium duration of contact event.
Counter Ruck from Distance (CRD)	Attacker arrives at ruck clearly ahead of defender resulting in defender accelerating into attacker to remove the attacker from the ruck. High collision velocity and low duration of contact event.

The fourth phase consisted of a series of double tackles where two tacklers attempted to tackle one ballcarrier. Players performed the tackles at different heights (one above waist tackler and one below waist tackler), however, no instruction was given regarding tackler height. Six double tackles were completed with different combinations of players involved in each tackle. Once testing scenarios had concluded, ITUs were stopped, sensors removed from players, and the data was uploaded to an online reporting tool (Protxx Inc, California, USA).

3.2.1. Data Analysis

Data was uploaded to an online reporting tool (Protxx Inc. US) and produced one comma-separated value (CSV) file per ITU used in the study. These files contained *x, y, z* axis for linear impacts and *x*, *y*, *z* axis for angular impacts. The linear acceleration data recorded to the online reporting tool was in m/s^2 which was converted to g before analysis and graphing. The angular acceleration data recorded to the online reporting tool was in units of degrees/s, and these were converted to rad/s^2. The data were analysed, and graphical representations produced using the Python programming language (Van Rossum & Drake, 2009) along with Matplotlib (Hunter, 2007) and Pandas (McKinney, 2010). Numerical data were presented using descriptive statistics calculated on the peak acceleration value achieved in each head acceleration event. Statistical analysis was conducted as outlined in Chapter 2. Normality of data was assessed visually using Q-Q plots and histograms, before being quantified using Shapiro-Wilk test. The significance of inter-group comparisons was assessed using One-way ANOVA or where applicable, a non-parametric equivalent. Post-hoc analysis was completed using a Bonferroni correction. Given that the ITUs record when a trigger threshold is attained (threshold not disclosed by the manufacturer), ITU readings for impacts were grouped if they were close together in time (<=200ms) to eliminate collusion between individual events. Head acceleration events were discarded if they failed to exceed either a linear acceleration threshold of 10g or an angular acceleration threshold of 4600 rad/s^2. These thresholds were chosen based on previous research indicating that maximum linear and angular acceleration during running and jumping was 9.54g and 4500 rad/s^2 (King et al., 2018). The threshold for acceleration magnitude was removed when attempting to discern other events, for example, running or changes of head direction, from contact events.

3.3. Results

Table 3.2. D*escriptive statistics of peak linear (PLA) and peak angular head acceleration (PAA) from different contact scenarios.*

	Linear Acceleration (g)						Angular Acceleration (rad/s^2)					
Event Type	Mean (SD*)	90th Percentile	75th Percentile	50th Percentile	Maximum	**Mean AUC**⸸**	Mean (SD)	90th Percentile	75th Percentile	50th Percentile	Maximum	**Mean AUC**
Filterable Events	11.75 (±1.77)	16.2	14.57	10.63	17.77	N/A	3868.72 (±1607.32)	6803.25	4658.18	3280.64	11337.71	N/A
Side Below Waist	22.95 (±1.89)	24.75	24.16	23.18	25.14	296.6	24974.93 (±12151.1)	29960.33	22441.93	20911.27	35972.59	290.7
Side Above Waist	18.16 (±3.35)	21.97	19.9	17.34	23.36	377.4	18579.12 (±10472.1)	28529.68	25300.59	19918.78	30682.4	384.1
Front Below Waist	18.83 (±1.34)	20.13	19.67	18.92	20.43	357.8	10899.43 (±4088.78)	15005.99	12512.41	8356.44	16668.38	385.6
Behind Below Waist	19.96 (±6.7)	26.33	24.26	20.82	27.71	251.5	11664.15 (±7622.91)	19425.99	15179.78	8102.76	22256.8	248.4
Rucks	20.94 (±5.25)	25.8	24.53	23.07	27.53	311.0	23801.5 (±15584.2)	31233.58	29204.74	19347.9	36488.85	222.1
Double Tackle	15.69 (±4.45)	21.07	18.77	15.2	23.29	332.0	10109.56 (±8361.89)	15824.72	10788.56	5780.68	32841.77	321.2

*Standard Deviation

**Area under the curve

⸸Linear Mean AUC is potentially an underestimate due to the limitations in maximum linear impact

Example Head Acceleration Event Acceleration Plots

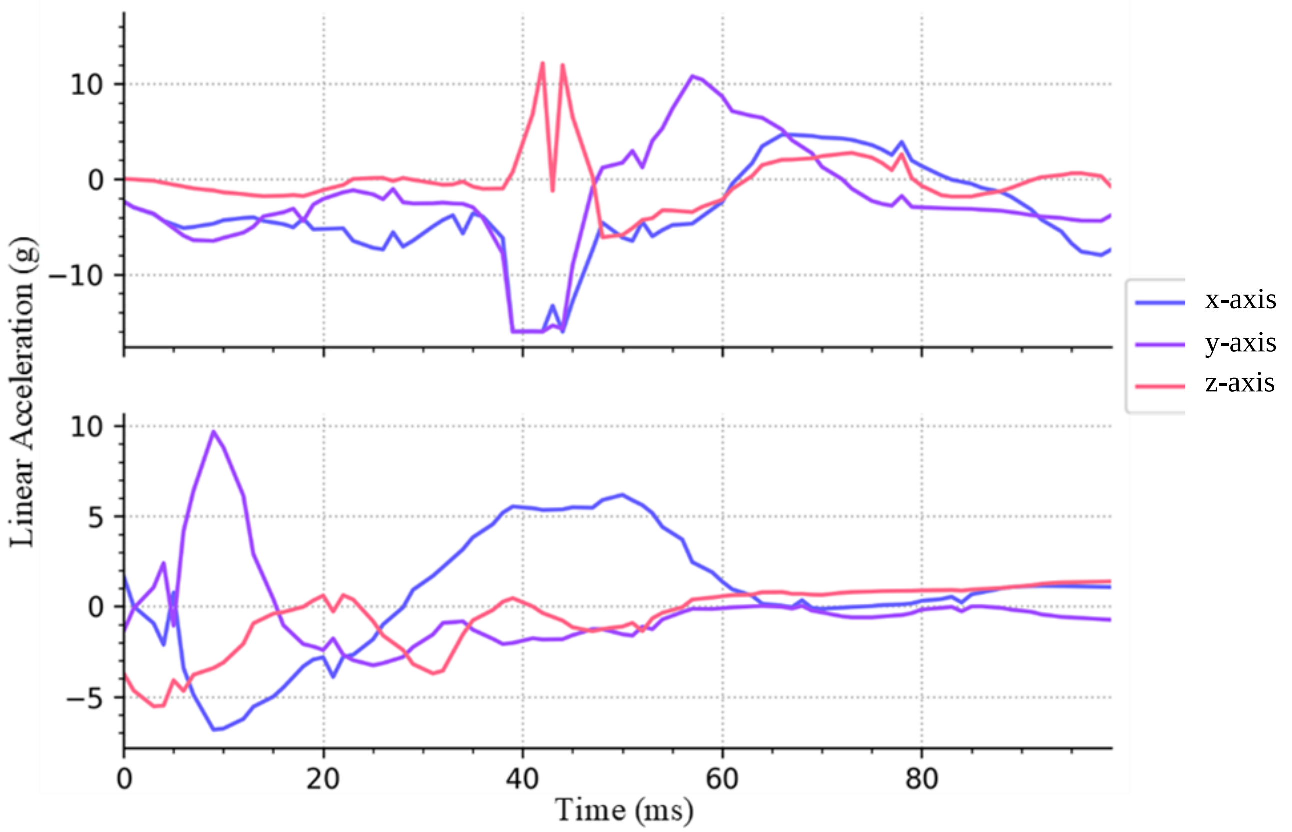

Figure 3.1. *Linear acceleration plot for side above waist tackle (Top: Ballcarrier & Bottom: Tackler).*

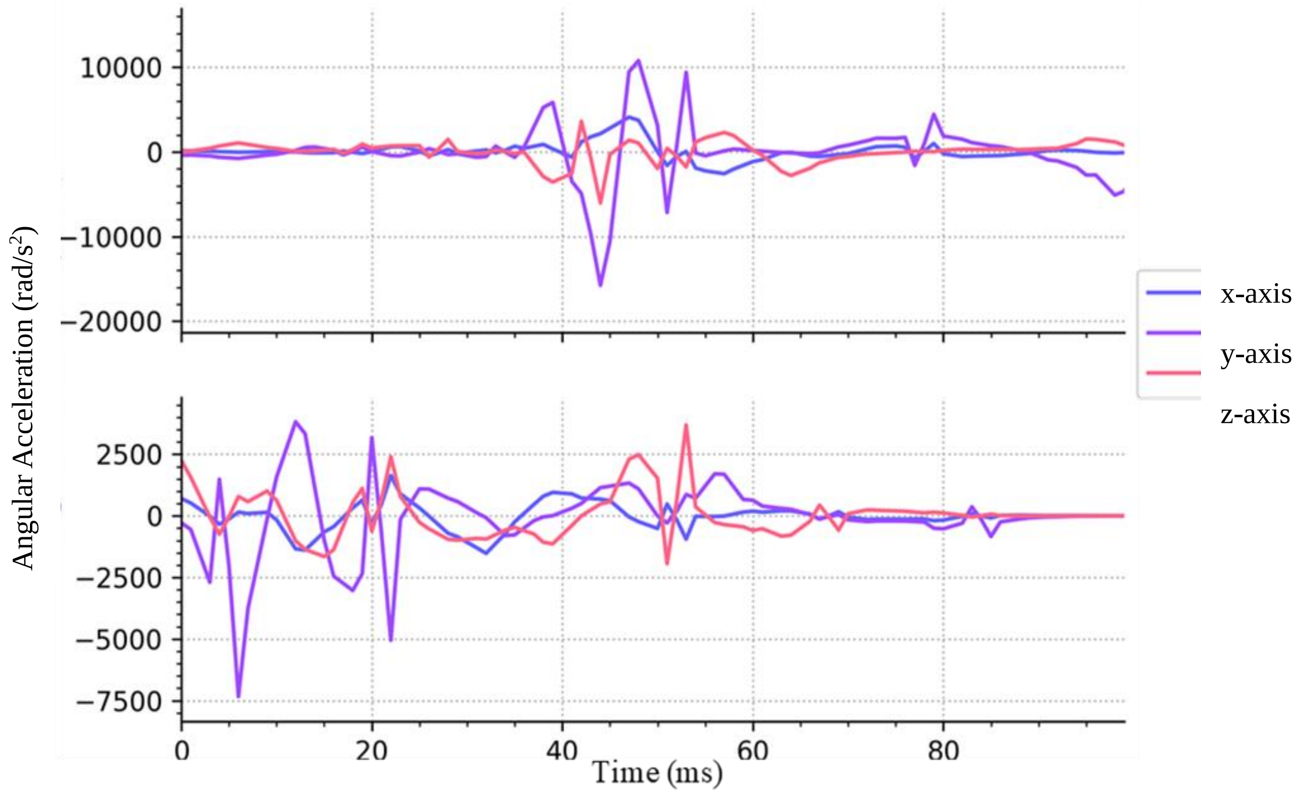

Figure 3.2. *Angular acceleration plot for side above waist tackle (Top: Ballcarrier & Bottom: Tackler).*

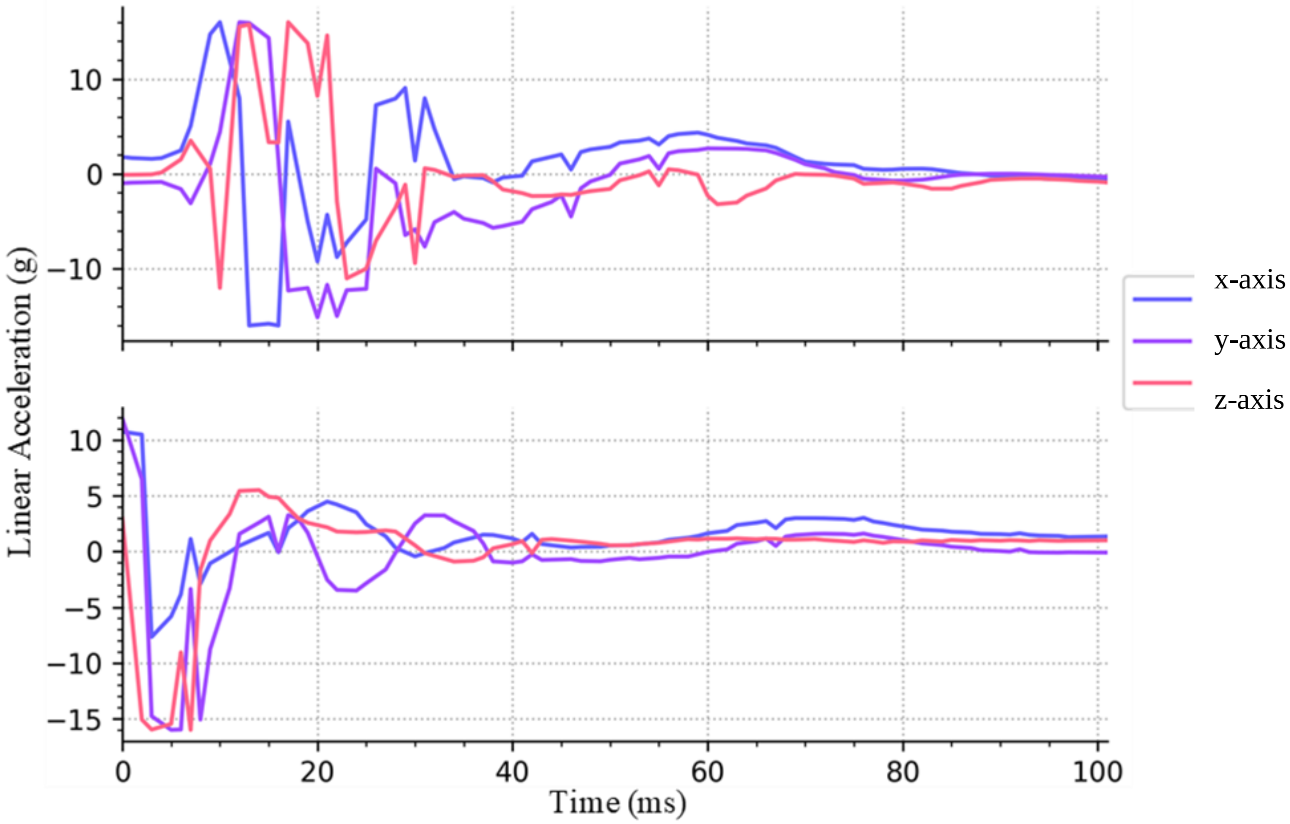

Figure 3.3. *Linear acceleration plot of a counter ruck (CR) (Top: Attacker & Bottom: Defender).*

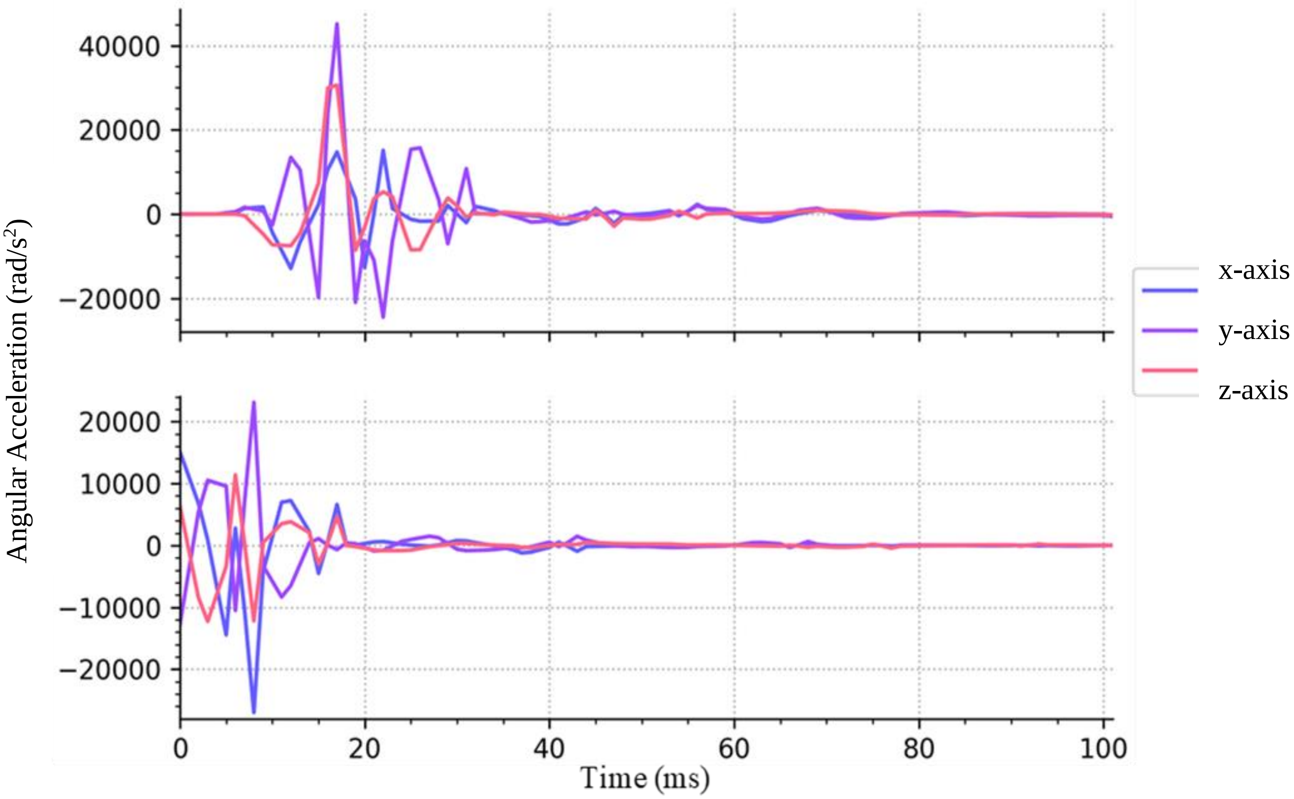

Figure 3.4. *Angular acceleration plot of a counter ruck (CR) (Top: Attacker & Bottom: Defender).*

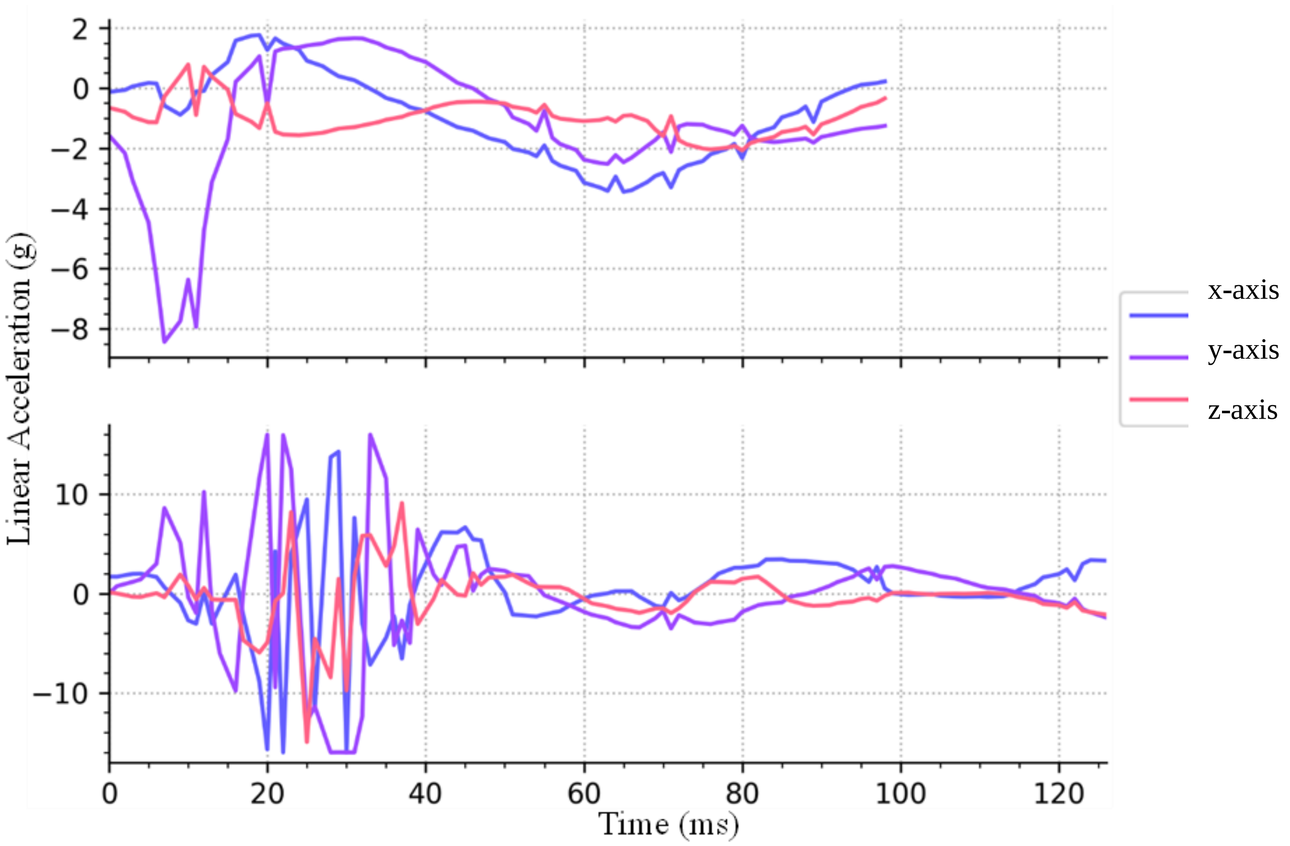

Figure 3.5. *Linear acceleration plot of a clearout ruck (CO) (Top: Attacker & Bottom: Defender).*

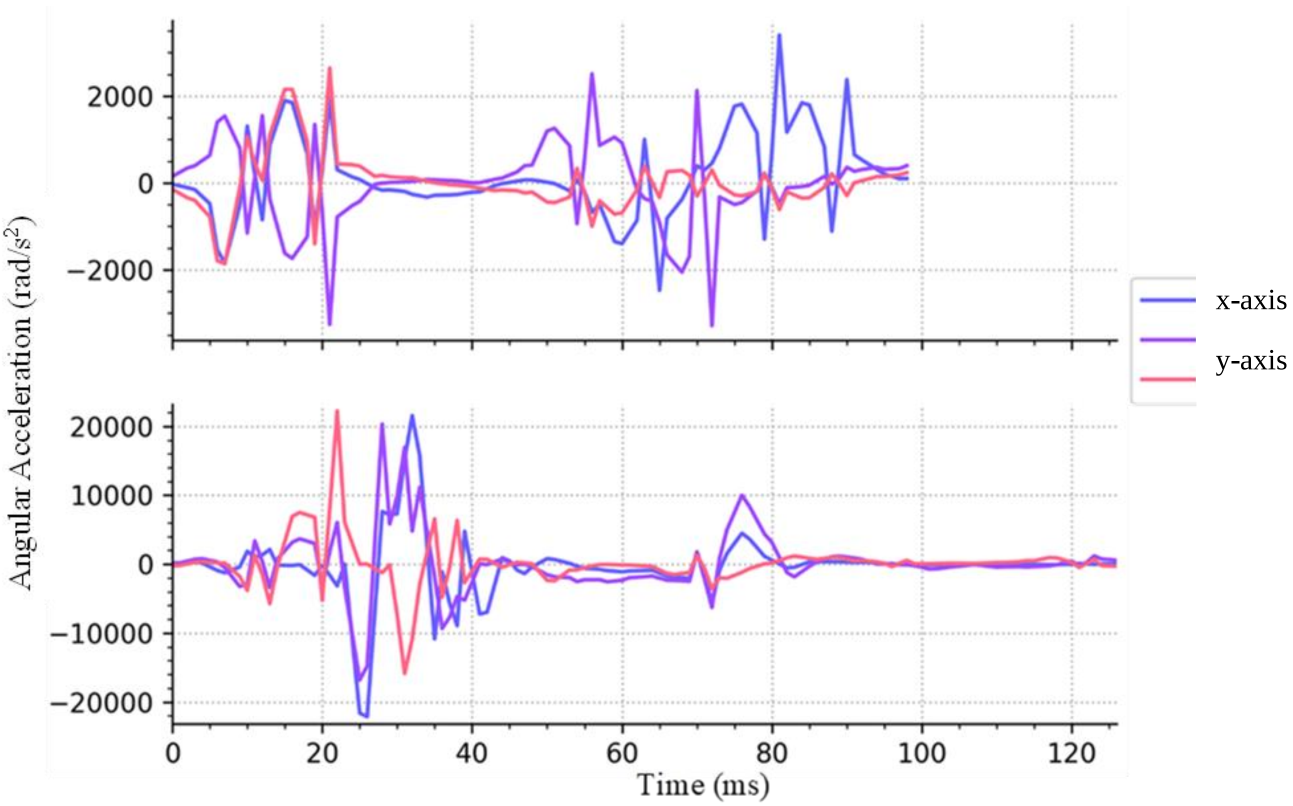

Figure 3.6. *Angular acceleration plot of a clearout ruck (CO) (Top: Attacker & Bottom: Defender).*

Acceleration Distributions

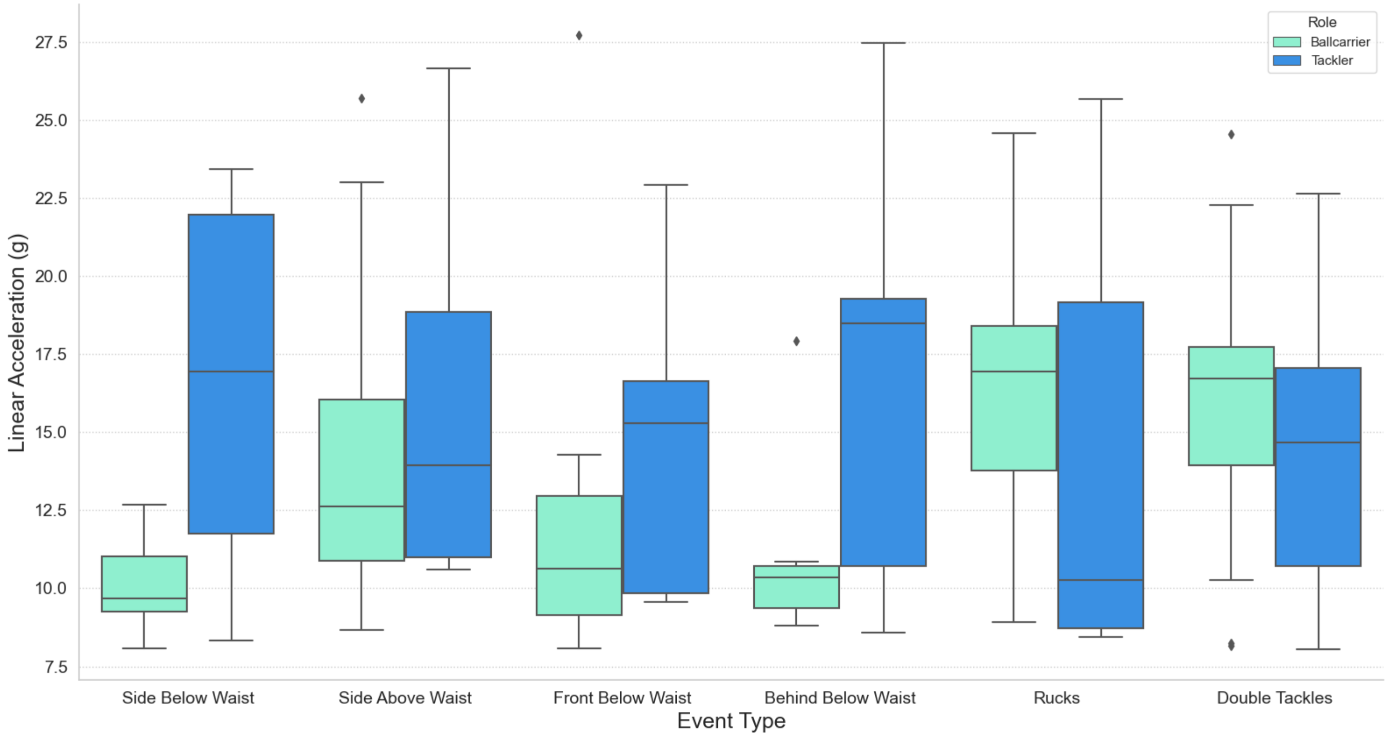

Figure 3.7. *Distribution of linear acceleration by contact event.*

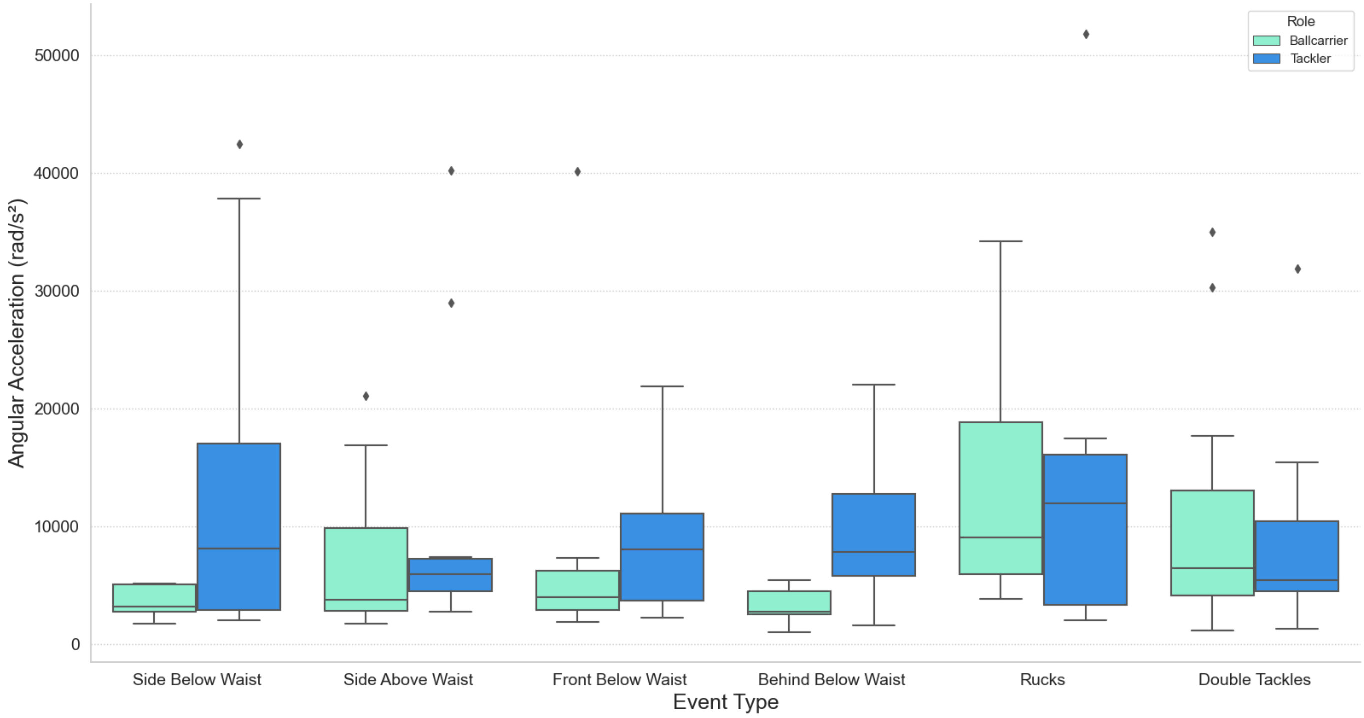

Figure 3.8. *Distribution angular accelerations by contact event.*

3.4. Discussion

This pilot study derived data to inform on rugby union player exposure to linear and angular head acceleration during common rugby union contact events. In addition, a thorough data analysis was conducted to inform on patterns in head acceleration telemetry from common rugby union contact events. This analysis could be used as reference for future studies and forms the basis for further data analysis in this thesis. It could also provide a reference point for further exploration of head acceleration in rugby, in addition to suggesting an indication of the potential magnitude of head accelerations that may be involved throughout the sport.

There were 198 total events with linear and angular acceleration elements that could be grouped as filterable events (running, change of direction, head shaking, falling) (n=83) one-on-one tackling (n=63), ruck scenarios (jackal, counter ruck, cleanout, counter from distance) (n=16), and double tackles (two tacklers and one ballcarrier).

The four one-on-one tackle types (SAW, SBW, FBW and BHBW) indicated the most variation in mean linear and angular head acceleration. SBW and BHBW tackles saw a high mean linear acceleration and higher 90th, 75th and 50th percentile values than SAW and FBW tackles. The linear acceleration mean difference observed between SBW-SAW ($p = 0.123$) and SBW-FBW ($p = 0.099$) was not considered statistically significant. The difference in linear head acceleration observed between SBW-BHBW was considered statistically significant ($p = 0.01$). However, SBW and BHBW tackles had lower AUC than SAW and FBW tackles suggesting a high peak acceleration but low event duration during SBW and BHBW tackles. SAW and FBW had notably higher AUC for both linear and angular acceleration therefore implying increased changes in head velocity (Table 3.2.), however these differences in AUC were not observed to be statistically significant. Tackles involving only two players were characterised by a short spike in linear acceleration, for both ballcarrier and tackler, lasting between 20ms to 40ms (Figure 3.1 & Figure 3.2). This peak was then followed by a decrease in linear acceleration on all axes until the end of event recording. In terms of magnitude of linear acceleration, the tackler experienced a greater peak in linear acceleration before the acceleration began for the ballcarrier – this is highlighted by the slight latency in recording between ballcarrier and tackler ITUs (Figure 3.1). The most observable differences in linear acceleration appeared to be in the abundance of secondary peaks for ballcarriers and the difference in duration of linear acceleration exposure, particularly evident in SAW (Figure 3.1). The SAW tackle showed a distinct durational difference between tackler and ballcarrier linear acceleration where the event ended for the tackler after 10ms but continued for ballcarrier for over twice this time. This was a common characteristic for all SAW tackles.

Identifying the characteristics of angular acceleration of different tackle types was more complex due to the inconsistency in event duration and magnitude. All ‘below waist’ tackles, irrespective of orientation, generated significantly higher angular acceleration magnitudes for tacklers ($p = 0.025$), whereas the contrary was true for ‘above waist’ tackles. All tackle types generated multiple changes in angular velocity throughout the duration of the event recording, in direct contrast, the peak magnitude of linear acceleration was seen at the beginning of each tackle. Other key observations included FBW tackles (Figure 3.8) being limited in median magnitude and variability of angular acceleration for both ballcarrier and tackler. A finding consistent with tackle mechanic observations and previous research (Willigenburg et al., 2016). In contrast, side tackles had the largest variation in angular acceleration magnitude between tacklers and ballcarriers of tackle types. The angular acceleration profile for the BHBW tackles saw the greatest inconsistency and latency between tackler and ballcarrier with the beginning of the tackle seeing a short peak of angular acceleration for the tackler followed by minimal further angular acceleration. In contrast, the ballcarrier experienced a delay in initial angular acceleration and then obtained a second notable acceleration later in the impact. The ballcarrier's peak angular acceleration was lower in magnitude when compared to the tackler ($p = 0.005$), however, over the whole tackle scenario, the ballcarrier's total exposure to angular acceleration was higher due to the secondary increase in acceleration.

The most identifiable features of rucks were the high mean angular acceleration (Table 3.2) and the large IQR in both linear and angular acceleration (Figure 3.7 & Figure 3.8). The high angular acceleration mean was contrasted with a low angular AUC. The duration of ruck event acceleration recording was significantly longer than the duration of tackle events (Figures 3.3 to 3.6). However, the lower AUC but high mean acceleration was indicative of a high initial acceleration and then minimal acceleration exposure once players had made contact. There were several observable differences between ruck types, most notably the largest variation in acceleration magnitude of all impact events with CRD and CR events having the highest total exposure.

There was notable variation in linear acceleration experienced by attacking and defending players during a CO ruck event (Figure 3.5). During a CO, the defending player arrived at the ruck area first, before being cleared by the attacking player. The first linear acceleration was received by the attacking player with notable acceleration on the y-axis but minimal acceleration on any other axis. The defending player then received multiple significant accelerations on different axis. The reactive nature of the linear accelerations seen in the defending player's plot suggests that as the player was not controlling the direction of contact, the defending player is more likely to experience accelerations on multiple planes. The defending player also received far greater angular acceleration on multiple axials (Figure 3.6), further emphasising the lack of control in contact the defending players had during rucks. However, none of these differences could be attributed any level of statistical significance (*p = 0.333*). The CR event appeared characteristically different from the CO event with the attacking player receiving the higher peak magnitude of linear and angular acceleration, however, the events could be considered somewhat identical. In the CR, the attacking player arrived first and was then removed from the ruck by the defending player. This suggests that the player who will experience the greatest magnitude and variation in linear and angular acceleration will be the most static player at the point of contact. Filterable events were clearly distinguished from contact events in terms of lower linear and angular magnitudes (Table 3.2.) ($p < 0.001$), with the majority not exceeding the 10g or 4600 rad/s^2 impact thresholds.

There are several considerations to make when interpreting the findings of this study. The first is that we were unable to quantify the true PLA and PAA that exceeded the maximum manufacturers linear and angular limits which was reached four times during the study. Due to this study and this thesis being largely directed towards subconcussive head acceleration, the limitations in PLA and PAA will not necessarily impact on findings due to linear and angular ITU limits exceeding what is currently suggested to be the minimum acceleration magnitude to generate a mTBI (King et al., 2018). Another consideration is the ITUs do not constantly record during their use and so there was the possibility of a slight latency between event recordings from ITUs on different players. The ITUs record using UNIX time, therefore giving a specific time stamp for the beginning of each event. However, to limit the possibility of event latency, the exact UNIX time of impact was recorded independently to ensure ITUs involved in the same event could be correlated. The third consideration is that play under controlled conditions is unlikely to be representative match play. The participants were instructed to complete the contact events at a lower intensity than normal match play due to an ethical consideration to protect the safety of all participants. The non-contact and contact events were performed under the instruction of a rugby union coach and by experienced players. Identification of ruck type by the rugby coach could be considered subjective as the description was based on live interpretation of the impact event and was not a predetermined ruck scenario. This permitted players to use whichever technique they preferred during the rucks thus allowing for more realistic impact events.

3.5. Summary, Limitations and Future Research

This study was conducted to characterise head acceleration telemetry for common rugby union events with the overall aim to provide guidance for future research using a larger sample, by characterising the magnitude and duration of head acceleration experienced during different contact and non-contact rugby union events. The study identified distinct differences in magnitude and duration of linear and angular head acceleration between contact and non-contact events particularly between tackle event types, some of which were considered statistically significant. However, due to the limitations with sample size and event intensity, the data presented should not be interpreted as indicative of head acceleration experienced during live match play.

3.6. Link to next Chapter

The most notable limitation with the data collected in this study was the small sample size of participants which subsequently resulted in a small sample of head acceleration events. This limited sample, in a ‘staged environment’, cannot be used to characterize live rugby union match events. To gather data that could be generalized and could be used to characterize head acceleration experienced by rugby union players, a larger sample size, collected during live match play could potentially produce results than are more indicative of the whole population. In the next chapter, contact events are examined using two full seasons of head acceleration telemetry, sampling in excess of 20000 events, or approximately 100x the sample size used in Chapter 3.

Chapter 4

Observations of contact and collision event frequency and magnitude in professional men's rugby union matches using head-mounted instrumented telemetry units

'The sooner we can educate, develop and work with younger players on tackle height, it makes the game safer for everybody… Everything is balance. You run the risk if you tackle high and get it wrong. I'd much rather we tackle low rather than a) somebody getting hurt or b) us losing somebody.'

- Kevin Sinfield OBE. England Rugby Union Defence Coach & Motor Neurone Disease Association Patron. b.1980

Chapter 4 - List of Tables & Figures

Figure 4.14. *Distribution of linear and angular head acceleration during lineout events represented by attacking and defensive types and player roles.*

Figure 4.15. *Distribution of linear and angular head acceleration during scrum events represented by attacking and defensive types and player roles.*

Figure 4.16. *Distribution of linear and angular head acceleration during maul events represented by player roles.*

4.1. Introduction

Tackle technique, tackle height, player collision orientation, and injuries associated with rucks have all gained attention in recent studies (Stokes et al., 2021; Tierney and Simms, 2018; den Hollander et al., 2023; Tierney et al., 2018) and in traditional sports media (Freeman-Powell, 2023; Kitson, 2023). Certain contact events, namely tackles and collisions, have often been associated with high magnitude head acceleration, whereas other contact events are more often associated with neck and shoulder injury (scrums) or lower limb injury (rucks) (West et al., 2021). This chapter attempts to highlight the frequency of contact and collision events in addition to the magnitude of linear and angular acceleration associated with each event, the player's role in the event, in addition to any orientation or collision height characteristics that may influence the acceleration magnitude of an event. In line with current literature (West et al., 2021; Tierney and Simms, 2018; Tierney et al., 2018), tackle events garner significant attention and are substantial focal point of this chapter, more so than other major contact events defined in the Laws of the Game (World Rugby, 2018).

The data from this chapter is from the main study sample, following the methods set out in Chapter 2, and does not include data collected during the pilot study (Chapter 3). The results presented in this chapter are a combined analysis of the head acceleration telemetry data collected during the two seasons of elite men's rugby union matches focussing on the prevalence, or frequency of different event types, and the magnitude of these events when players are involved in different roles, collision heights or in an offensive or defensive capacity.

4.2. Contact Event Frequency

Table 4.1. *Frequency of valid, non-contact and false positive events.*

Event	Frequency
Consistent Direction Run	4059
Multi Direction Run	2018
False Positive	2992
Contact or Collision Event (Valid Events)	11330
Total	20399

Of the 20339 events that exceeded the linear threshold of 10G or the angular threshold of 4600rad/s^2, 55.5% were identified via primary and secondary video validation to be valid contact or collision events either as defined in the Laws of the Game (World Rugby, 2018) or as spurious collision events between players, objects or the ground identified by both reviewers. Consistent direction runs constituted 19.9% of the total events with multi directional runs equating to 9.9% of total events. False positives consisted of IMU triggers, where thresholds were exceeded but no event could be identified by any video reviewer or the player wearing the IMU was not identifiable from the video angles available for each match.

Table 4.2. *Frequency of macro event classification of positively identified head acceleration contact or collision events.*

Contact Event	Frequency
Collision	2212
Lineout	460
Maul	1232
Ruck	2783
Scrum	869
Tackle	3774

As expected, the modal contact event was the tackle, followed by rucks and then spurious collisions either with the ground or another player. Of the 11330 video validated contact events, 33.3% were tackles, 24.6% were rucks, 19.5% were collisions, 10.8% were mauls, 7.7% were scrums, and 4.1% were lineouts.

Table 4.3. *Frequency of micro and nano event classification of positively identified head acceleration contact or collision events (excluding rucks and tackles).*

Contact Event	Micro Classification (Type)	Frequency	Nano Classification (Role)	Frequency
Collision	Player-Player	1321	-	-
	Player-Ground	875	-	-
Lineout	Attacking	323	Jumper	156
			Lifter	120
			Support	47
	Defending	137	Jumper	57
			Lifter	52
			Support	28
Maul	Ballcarrier	73	-	-
	Support	1159	-	-
Scrum	Attacking	441	Front Row	159
			Second Row	106
			Back Row	176
	Defending	428	Front Row	160
			Second Row	94
			Back Row	174

Table 4.3. represents the frequency of non-tackle or ruck valid contact events and the associated minor categorisations. Collisions that did not result in a defined contact event contributed significantly to the total event frequency with majority of the collision events being between two or more players with the remainder between the player and the ground. Valid events identified by reviewers as lineouts were categorised as defensive and offensive

and then further categorised as role within each lineout event. Overall, more attacking lineouts resulted in a positive trigger than defending lineout. However, in both attacking and defending lineouts, the jumper was the player who most often resulted in a validated head acceleration event. Majority of the maul events were represented by support players or non-ball carrying players with the difference in sample size between support players and ballcarriers making comparison of the groups statistically challenging due to issues with type I error rates in any statistical test that assumes equal variances. The frequency of attacking and defending scrums resulting in a validated head acceleration event was similar with front row players and back row players resulting in more trigger events than second row players. However, the number of players in a scrum classified as front row (3), second row (2) and back row (3) differs, which could distort valid event frequency.

Table 4.4. *Frequency of positively identified micro and nano ruck event classifications.*

Micro Classification (Type)	Frequency	Nano Classification (Role)	Frequency
Clear-out (CO)	2117	Attacking	1417
		Defending	201
		Guard	113
		Floor	386
Counter-ruck (CR)	242	Attacking	54
		Defending	139
		Guard	13
		Floor	36
Counter-ruck from distance (CRD)	59	Attacking	45
		Defending	7
		Guard	2
		Floor	5
Jackal (JKL)	365	Attacking	65
		Defending	281
		Guard	4
		Floor	15

The vast majority of valid ruck events were classified as clear-out types with the least common ruck type classification being counter-ruck from distance. Over half of the players involved CO rucks were seen as attacking players, in addition to *CO Defending* events equating to the third most modal event nano classification. Guard roles in CO events were also relatively common when compared to guard roles in the other ruck micro classifications.

However, this metric could have been distorted due to the high volume of CO type ruck. A more representative means to compare the active role data in Table 4.4 might be to consider the nano classifications of each ruck event, independently from that of their micro classifications. For example, there were 1581 *attacking*, 629 *defending*, and 132 *guard* nano classifications. The frequency profiles for CR and JKL ruck types were relatively similar with the modal role for players involved was as a defender. Similar frequencies for *CR attacking* and *JKL attacking* were observed in addition to similar minor frequencies between CR, JKL and CRD *guard* and *floor* events. Comparatively few rucks indicated players, involved in this study or otherwise, entering the ruck area from a significant distance (CRD). Although, when these events did occur, 76% of CRD events involved a player in an attacking role creating or preventing a counter-ruck occurring. Active roles within all ruck events (attacking, defending or guarding) accounted for 84.2% of validated ruck event types.

Table 4.5. *Frequency of positively identified micro and nano tackle event classifications.*

Micro Classification (Role)	Frequency	Nano Classification (Orientation)	Frequency
Ballcarrier	1706	Front	722
		Side	387
		Behind	173
		Double	424
Tackler	2068	Front	919
		Side	608
		Behind	263
		Double	278

There was a difference of 362 between the frequency of ballcarrier tackle events and tackler tackle events. For both ballcarriers and tacklers, the front orientation was the most common, followed by tackles from the side, and then double tackles. Tackle orientation with the lowest frequency was tackles made or attempted from behind the ballcarrier.

4.3. Contact and Collision Event Magnitude

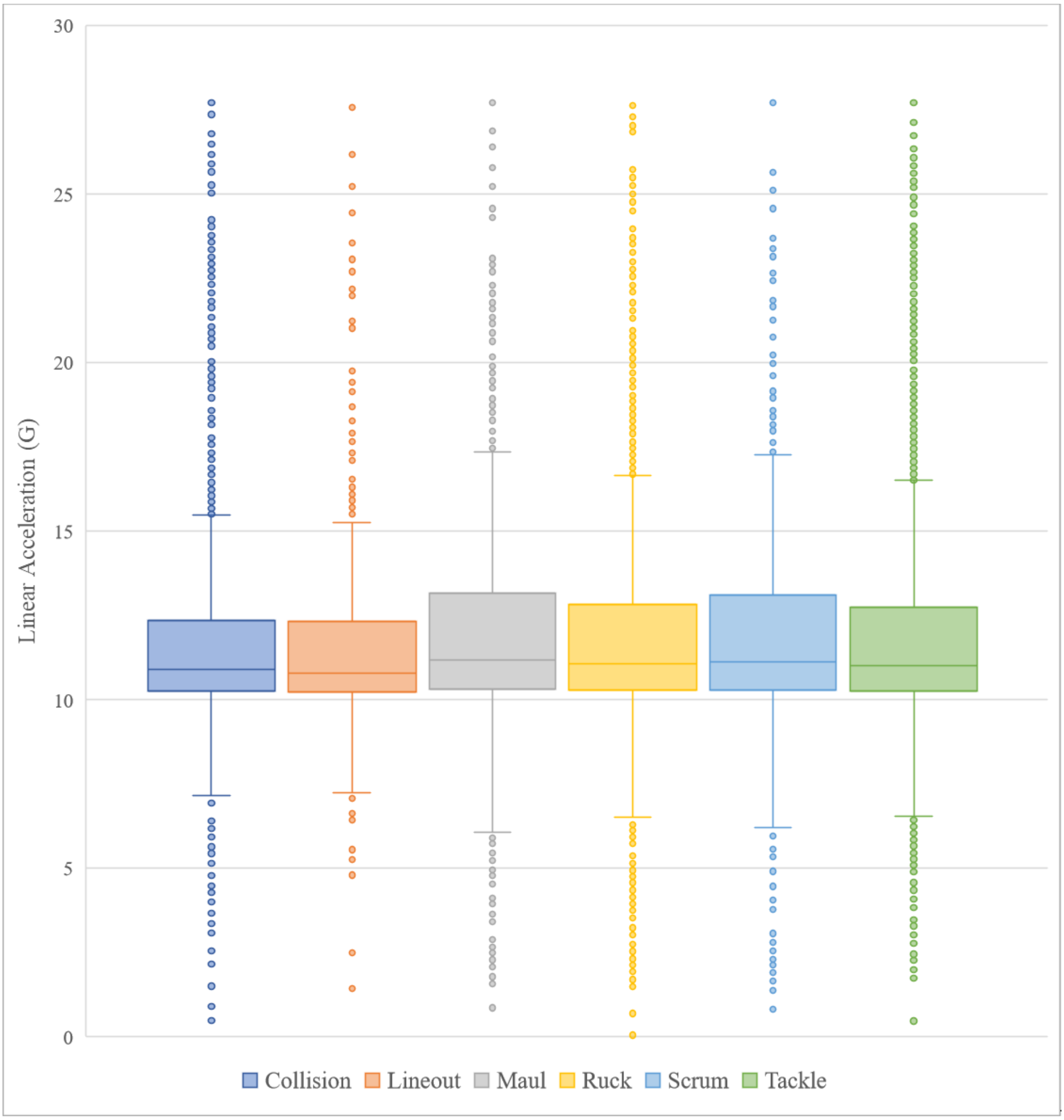

Figure 4.1. *Distribution of peak linear acceleration (PLA) of the head recorded during positively identified macro contact or collision event classifications.*

From a macro event classification perspective, there was minimal difference between the peak linear acceleration (PLA) of the head during different contact events for the players in this study. The major contact events had the following median and IQR PLA values: lineout

(10.8g (2.1)), maul (11.43g (3.0)), ruck (11.1g (2.66)), scrum (11.1g (2.89)), and tackle (11.0g (2.61)). Correlations coefficients were used to indicate any statistical association between the PLA experienced during the different contact events. All contact event variables were considered non-parametrically distributed, therefore, a series of Mann Whitney-U tests were used to assess the PLA data. No statistically significant differences were observed between any of the major contact event macro classifications.

All macro classification contact events, with the exception of lineouts, reached the maximum limit on the ITUs (27.71g). Mauls, rucks and scrums achieved the maximum PLA value once, whereas tackles reached the threshold on three occasions. Collisions not constituting an official contact event had a mean PLA of 11.77g ±3.12 similar to the other macro classifications. Variation was observed in the distribution of head accelerations of contact events with the greatest IQR value seen during maul events and the smallest variation observed during lineout events. Fig. 4.1. appears to indicate a notable frequency of outliers, a trend that can be observed on several figures later in this chapter, however, due to the volume of data points, only approximately 4% of events are considered outliers.

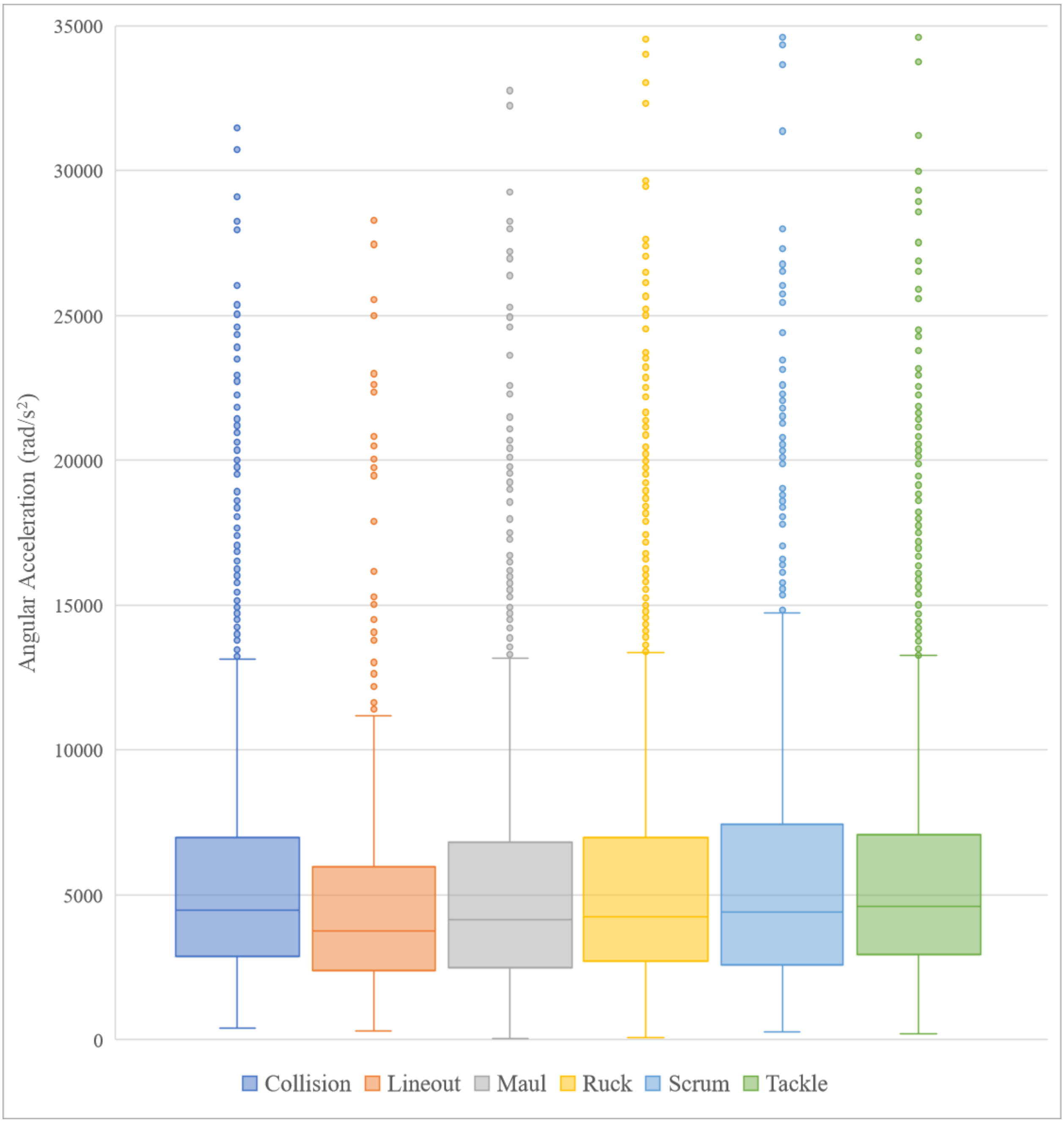

Figure 4.2. *Distribution of peak angular acceleration (PAA) of the head recorded during positively identified macro contact or collision event classifications.*

Similar to the experience of PLA, there is minimal difference between the peak angular acceleration of the head (PAA) during different contact events for the players in this study. The major contact events had the following median PAA: lineout (3754.37rad/s^2 ±3593.4), maul (4130.97rad/s^2 ±4216.71), ruck (4452.42rad/s^2 ±4866.68), scrum (4121.43rad/s^2

±4619.48), and tackle (4528.46rad/s^2 ±3847.35). Correlation coefficients (Spearman's ρ) was used again to assess the association between contact events but from a PAA capacity. There were no associations of note therefore indicate no similarity between PAA between contact events. The maximum PAA threshold of the ITU (34606.16rad/s^2) was only achieved on three occasions; once during a scrum event and twice during tackle events. Collisions had a mean angular acceleration of 5618.56rad/s^2 ±4340.64 which was again similar to the other main contact event classifications. Unlike observations of PLA, the variation of PAA during events did not follow the trend of "greater median values result in greater IQR values", but instead saw ruck events have the greatest IQR value (4857.22rad/s^2) and then lineout events have the smallest IQR.

From Fig 4.1. and Fig 4.2. it could be suggested that due to the high median PLA that tackles have the highest linear acceleration load and scrums result in the highest angular acceleration load. However, the large variation, in particular concerning the angular acceleration data makes it difficult to conclude this with any confidence. Only scrum and tackle events reached both the linear and angular acceleration thresholds. This does in some respects support the suggestion that these events have the propensity for higher acceleration exposure, however, the limited frequency of threshold occurrences does not add significant weight to this argument. A contact event area where it could be suggested that is relatively low in terms of acceleration exposure was during lineout events. Lineout events saw the lowest median linear acceleration and saw no significant association with any other contact event. Lineout events also had the lowest median PAA of all the contact events. The similarities between linear acceleration seen between lineout events and maul events could also be due to the proclivity for a lineout to develop into a maul once the lifted players have been returned to the ground. Overall, the relatively large IQR values make it difficult to discern any true differences between macro classifications beyond unsubstantiated assumptions. However, the following sections will separate the players roles, collision types and where relevant, the body position of the player to provide clarity beyond that of the macro classifications.

4.3.1. Tackle Magnitude: Roles, Orientation and Height

As suggested in the introduction to this chapter, the tackle in both the professional and community levels of rugby union has received significant media and academic attention throughout the duration of this study. Both anecdotally from discussion with players and coaching staff, and from observing published research, there remains significant confusion concerning differing tackle styles, heights, and orientations and which ultimately result in higher head acceleration exposure or higher risk of mTBI. It has been suggested that the tackler is at the greatest risk of having to be removed from the pitch for an HIA (Tierney and Simms, 2018), going on further to suggest that a tackler should aim to make contact with the ball carrying player below the upper trunk (Hendricks et al., 2014). Similar research has confusingly indicated that tackling of the upper leg area can potentially lead to an increased risk of removal for HIA and potentially leading to the conclusion that a combination of lower trunk and lower leg tackles are the safest for tackler and ballcarrier. In the landmark Championship rugby study conducted in 2018 which saw tackle height for Championship cup fixtures use a reduced tackle height to in line with the armpits, suggested that there was a reduction in the frequency of tackles where head, neck or shoulder were the first points of contact. However, the study did report an increase in the frequency of confirmed mTBI events for tackling players when attempting tackles at height (mid-trunk) that had previously seen a reduction in HIA removals for tacklers (Stokes et al., 2021).

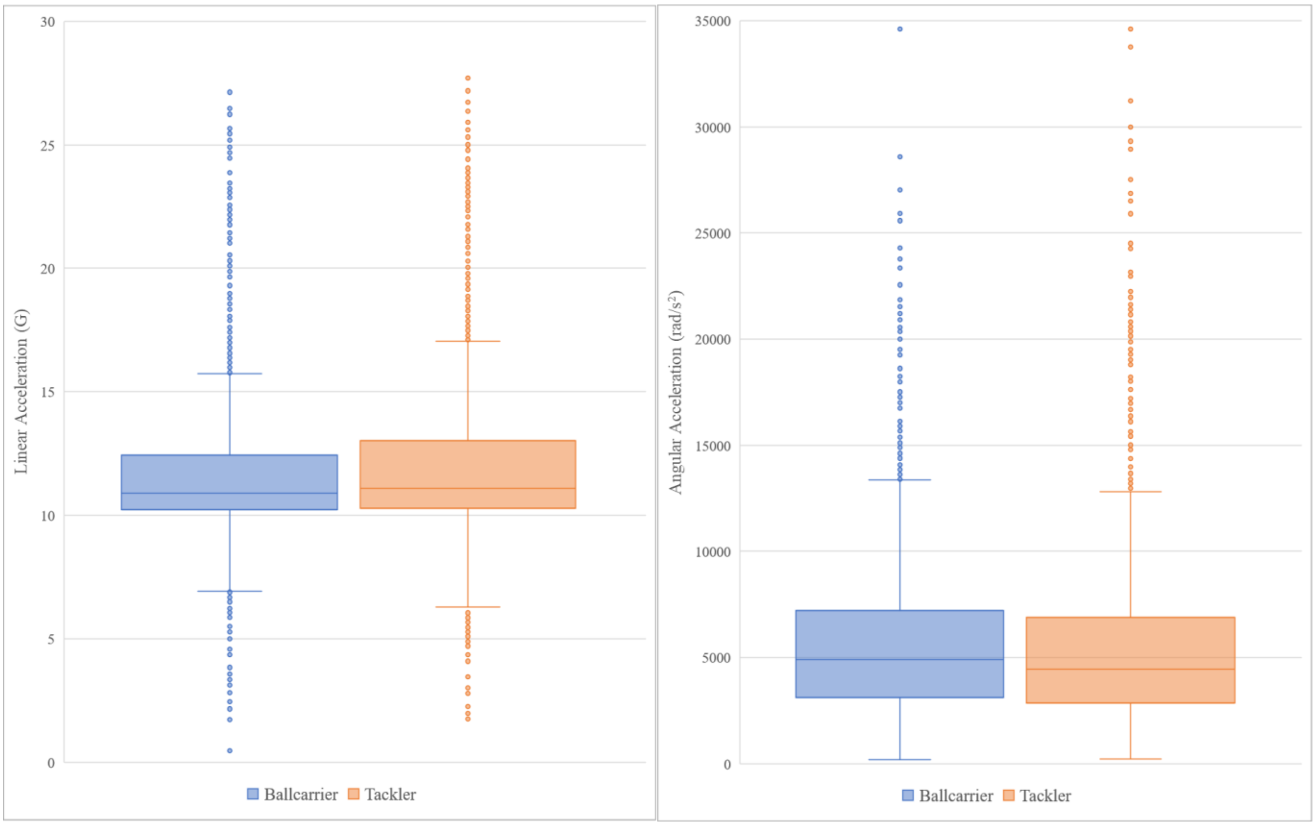

Figure 4.3. *Distribution of peak linear (PLA) and peak angular acceleration (PAA) recorded during tackle events represented by player role during the contact event.*

The most basic question that is discussed regularly in academic literature (Hendricks et al., 2014; Quarrie and Hopkins, 2008; Stokes et al., 2021; Tierney et al., 2018; Tierney and Simms, 2017; Tierney and Simms, 2018) and colloquially at elite and community clubs is often focussed on ballcarrier versus tackler exposure to head acceleration. As can be observed from Fig 4.3., both ballcarrier and tackler experienced similar PLA and PAA magnitudes but with the tackler (12.14g (2.71)) experiencing slightly greater PLA than the ballcarrier (11.71g (2.21)), whereas the reverse is correct for PAA (BC = 5783.28rad/s^2 (4048.56)), T = 5622.6rad/s^2 (4133.4)). In terms of data dispersion, the ballcarrier PLA and PAA IQR is less than the PLA and PAA IQR of the tackler. This indicates a greater level of variability in the head acceleration experienced by the tackler. Maximum PLA and PAA ITU thresholds were both achieved by tacklers, but only maximum PAA threshold was achieved by ballcarriers.

Histograms and Q-Q plots were used to visually inspect data for normality. In addition, Kolmogorov-Smirnov and Shapiro-Wilk ($p < .001$) tests for normality both indicated that the data was non-parametrically distributed, therefore a Mann Whitney-U test was used to establish significance of the difference in head acceleration experienced by ballcarriers and tacklers. The Mann Whitney-U test indicated that the difference of PLA and PAA between tackler and ballcarrier to be statistically significant (Linear: 0.43g, $p < .001$, Angular: 160.68rad/s^2, $p = .004$). The players involved in tackle events as the tackler experienced higher median PLA and greater variability in PLA and PAA than their ball carrying counterparts. In contrast, the ball carrying players indicated a higher median PAA but a small variability in head acceleration in both linear and angular planes. The differences between ballcarrier and tackler can be considered statistically significant.

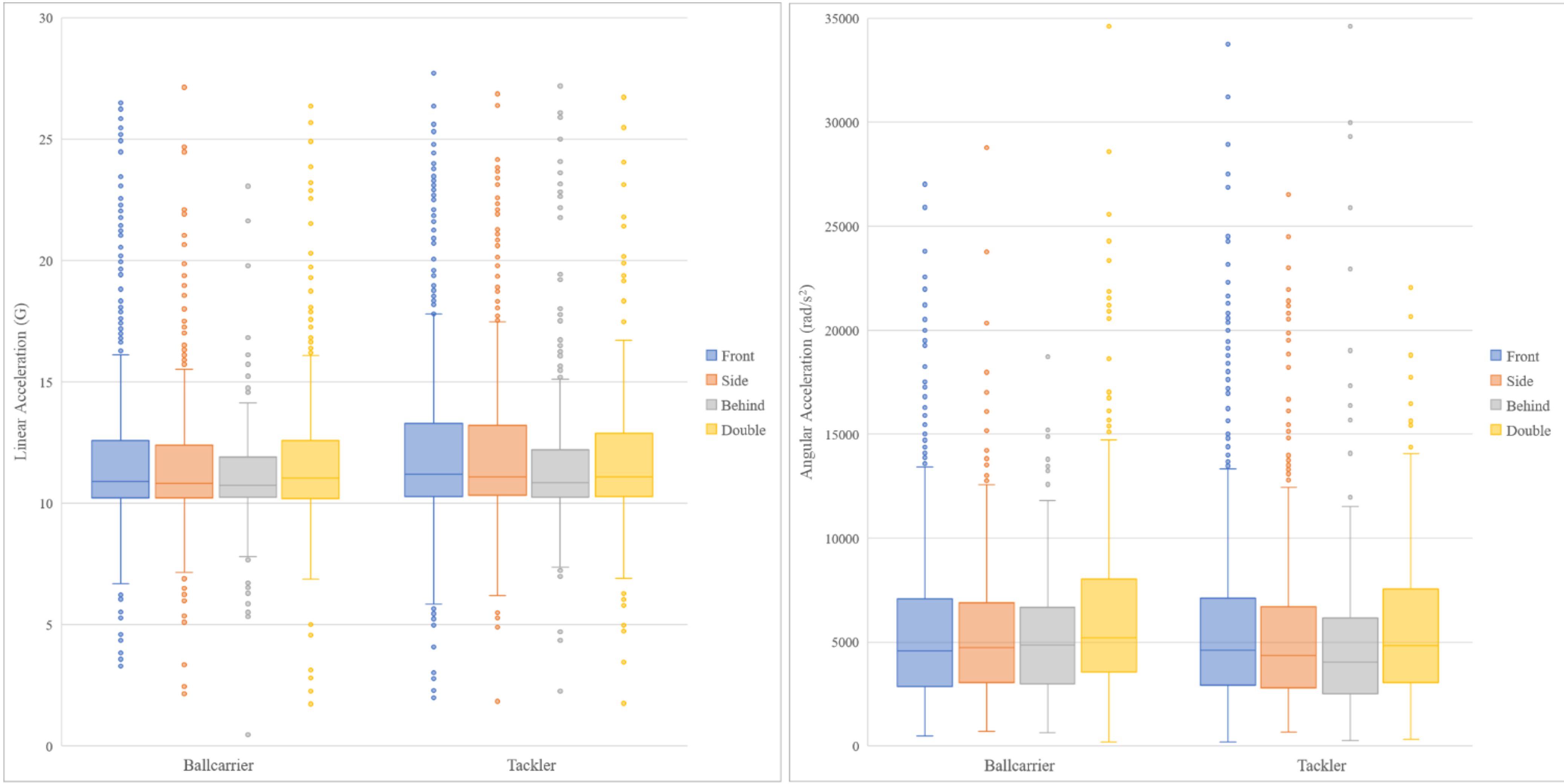

Figure 4.4. *Distribution of peak linear (PLA) and peak angular acceleration (PAA) recorded during tackle events represented by tackler-ballcarrier orientation during the contact event.*

The orientation of the tackler has had little attention in recent research with the exception of work completed by Davidow et al. (2018) and den Hollander et al. (2023) which have influenced the interpretation and presentation of the data used in this chapter as similar orientation groupings were used in these previously conducted studies. Fig. 4.3. indicated significant differences in the PLA and PAA between ballcarrier and tackler. Fig. 4.4. indicates the differences between tackler and ballcarrier head acceleration separated into ballcarrier-tackler orientations. The PLA for ballcarriers and tacklers was represented in four orientations: front (*BC* = 11.84g ±3.34, *T* = 12.29g ±3.56), side (*BC* = 11.65g ±2.98, *T* = 12.15g ±3.18), behind (*BC* = 11.51g ±2.48, *T* = 11.88g ±3.4) and double (*BC* = 11.75g ±3.21, *T* = 11.85g ±3.15). The PAA for ballcarriers and tacklers was represented using the same orientations: front (*BC* = 5561.94rad/s^2 ±3950.69, *T* = 5806.66rad/s^2 ±4657.06), side (*BC* = 5565.49rad/s^2 ±3776.14, *T* = 5434.81rad/s^2 ±4034.65), behind (*BC* = 5275.64rad/s^2 ±3100.15, *T* = 5142.37rad/s^2 ±4717.62), double (*BC* = 6581rad/s^2 ±4849.35, *T* = 5879.846). The most clearly observable difference in terms of descriptive statistics from Fig. 4.4., occurred concerning maximum PLA and PAA during the various orientations. Of the three tackle events that achieved the PLA maximum threshold, all three occurred to tacklers during front orientation events. The maximum PLA for the other orientations ranged between 23.05g (*BC_behind*) to 27.18g (*T_behind)*. Maximum PAA threshold was achieved by a ballcarrier during a double tackle and by a tackler whilst making a tackle from behind. The maximum PAA for the other orientations ranged between 18721.5rad/s^2 (*BC_behind*) to 33752.02 (*T_front)*. Variable differences and statistical significances were calculated using Mann Whitney-U tests and Friedman's tests, due to the non-parametric nature of the distribution of some variables and are represented in fig. 4.5. and fig. 4.6. A logarithmic transformation of the data was considered, in order to utilise parametric independent sample tests, however, using the telemetry data in raw format is often considered more representative and there is no guaranteed that a logarithmic transformation would have resulted in normalised data (Feng et al., 2014).

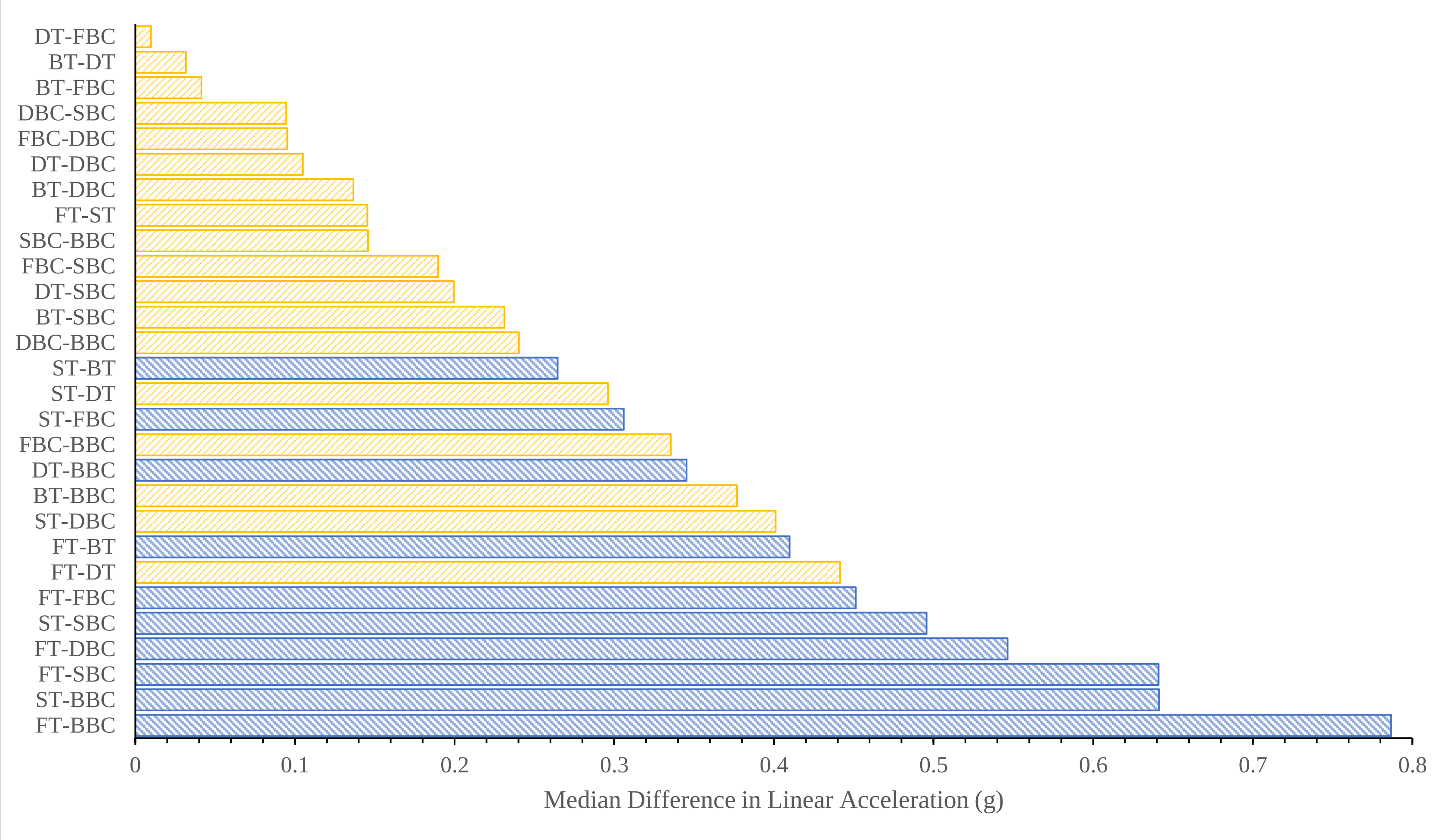

Figure 4.5. *Median difference in peak linear head acceleration (PLA) and statistical significance of tackle event orientation-role characteristics.*

FBC = front ballcarrier, FT = front tackler, SBC = side ballcarrier, ST = side tackler, BBC = behind ballcarrier, BT = behind tackler, DBC = multiple (tacklers) ballcarrier, DT = multiple (tacklers) tackler

 = Significant ($p \leq 0.05$),  = *Not Significant* ($p > 0.05$)

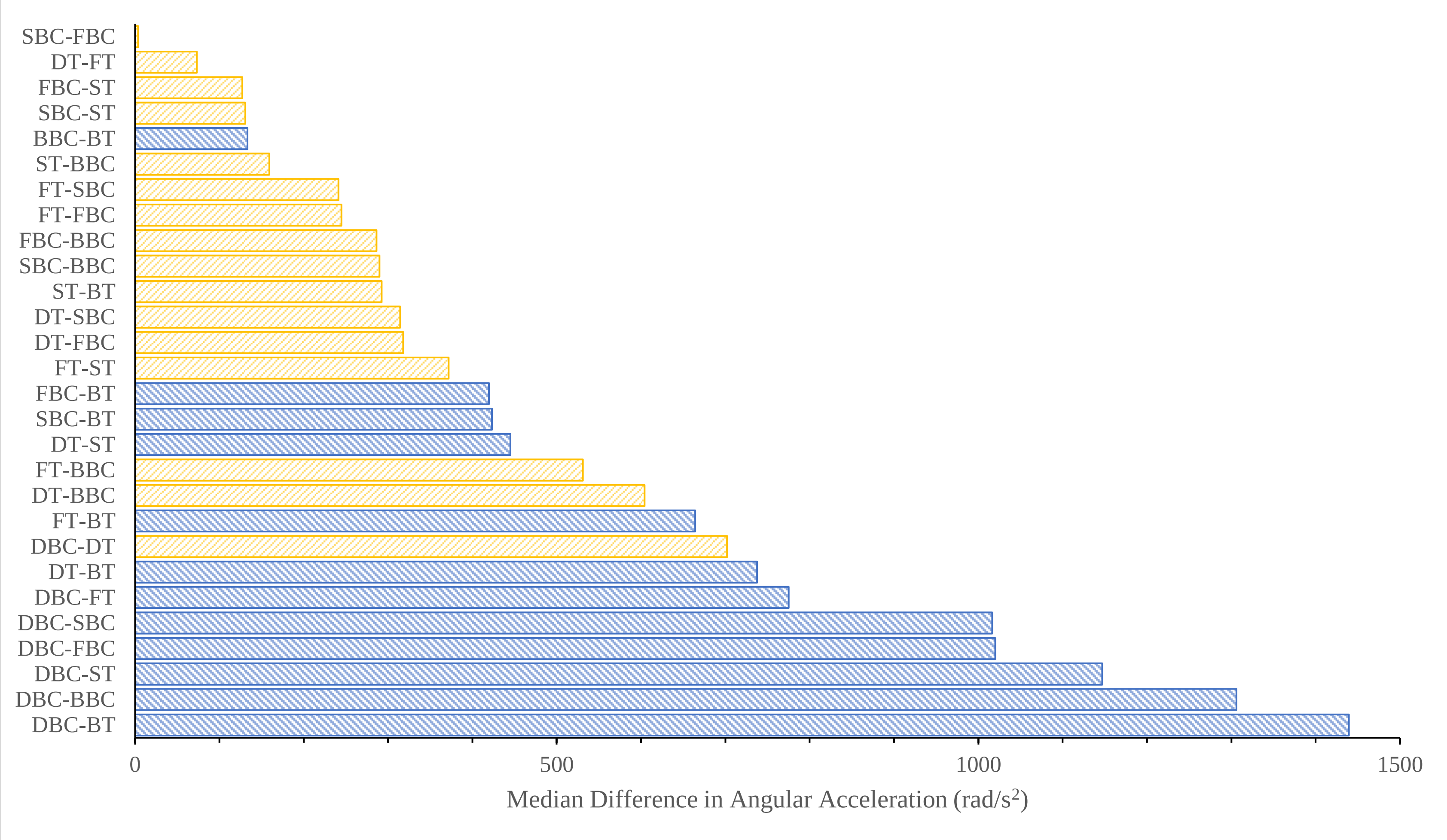

Figure 4.6. *Median difference in peak angular head acceleration (PAA) and statistical significance of tackle event orientation-role characteristics. FBC = front ballcarrier, FT = front tackler, SBC = side ballcarrier, ST = side tackler, BBC = behind ballcarrier, BT = behind tackler, DBC = multiple (tacklers) ballcarrier, DT = multiple (tacklers) tackler*

 = Significant ($p \leq 0.05$),  = *Not Significant* ($p > 0.05$)

The orientation-role characteristics are ordered in fig. 4.5. and fig. 4.6. by magnitude of median difference in head acceleration and the colour box denotes whether the outcome of the statistical test was significant or not. These figures denote multiple pairwise comparisons that highlight which tackle orientation-role combinations have a greater PLA or PAA. For example, the PLA experienced by a ballcarrier during a front orientated tackler is statistically significantly less than the PLA experienced by the tackler. In contrast, the PAA experienced by the ballcarrier during front orientated tackles is again less than that experienced by the tackler, but this result was not considered significant. The most obvious trend that can be observed concerning player exposure to linear head acceleration is that the PLA for front orientated tacklers is statistically significantly greater than all other orientation-role combinations except during the comparison between *side_T* and *front_T* where there was no significant difference ($p = 0.570$). This highlighted that players who are the tackler in front orientated tackles experience significantly more linear head acceleration than players who perform tackles from behind ($p = 0.013$). Front orientated tacklers also experienced significantly more PLA than all ballcarriers irrespective of orientation. There was a large mean difference between PLA for front tacklers and double tacklers, however, this difference was not considered statistically significant. Similarities between front orientated tacklers and double tacklers occurred throughout the study, potentially attributed to the idea that in many double tackles at least one tackler is usually front orientated to the ballcarrier.

The general trend observed from tackle events indicated statistically higher PAA for ballcarriers when compared to tacklers even at an intra-orientation level. The only exception was a not significant result between ballcarriers and tacklers during double tackles ($p = 0.096$). Ballcarriers during double tackles experienced statistically significantly more angular acceleration than players involved in other ballcarrier orientations (front: $p < 0.001$, side: $p = 0.004$, behind: $p = 0.008$). Tackle events where a tackler experienced higher PAA than a ballcarrier only occurred when front, side or double orientations were compared with behind orientated ballcarriers, but none of these results were consider significant (front: $p = 0.945$, side: $p = 0.46$, double: $p = 0.241$).

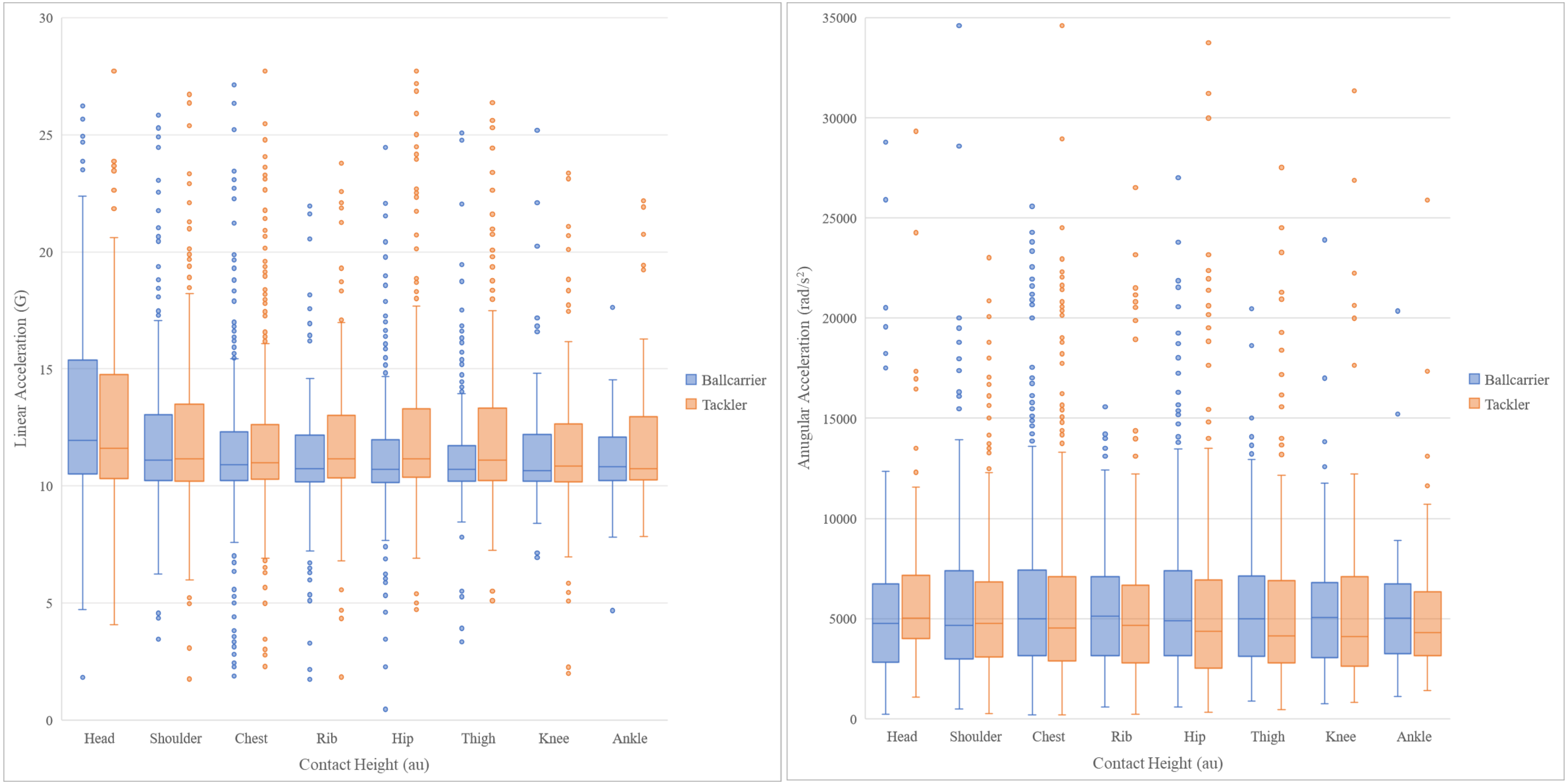

Figure 4.7. *Distribution of linear and angular head acceleration at various tackle heights represented by role as ballcarrier or tackler.*

Tackle events were separated into eight height categories with the height of the tackle defined by the point of contact on the body of the player wearing the ITU. Events in fig. 4.7. are also separated into tackler and ballcarrier roles for clarity. As can also be observed from fig. 4.7., the median PLA at contact heights shoulder to knee are greater for the tackler, whereas the figure suggest that the median PLA is greater for the ballcarrier when the contact height is at the head or the ankle. In terms of PAA, the median appears to be greater for the tackler at the head and shoulder contact height and then greater for the ballcarrier from the chest downwards. Maximum ITU PLA threshold was achieved at three contact heights: head, chest and hip, all by tacklers. Maximum PAA ITU threshold was achieved at two contact heights: shoulder for a ballcarrier and chest for a tackler. With the exception of the PLA experienced by ballcarriers where the tackle height was at the head, the variability, indicated by IQR values, in PLA experienced at all tackle heights was greater for the tacklers. In contrast, difference in the variability in PAA was more limited even at an intra-height level between players performing the different roles in the tackle.

All combinations of tackle height and tackle role were assessed using a series of pairwise comparisons to indicate significant differences between the head acceleration experience at the eight different contact height divisions. For the ballcarrier, PLA when the contact was at the ballcarrier's head was statistically significantly higher than when at all other contact heights. This was true between head and all other tackle heights when $\alpha = 0.01$, *CI = 99%* and true for head to chest-knee when $\alpha = 0.001$, *CI = 99.9%*. Head-ankle pairwise comparison was not statistically significant at the lower α value. Ankle tackles have a notably lower frequency compared to other tackle heights so this could potentially be a suggestion for the lack of significant difference between head-ankle tackles. For the tackler, PLA did not differ significantly ($\alpha = 0.05$, *CI 95%*) at any contact height.

In terms of angular head acceleration, for the ballcarrier there were no statistically significant differences (*α = 0.05, CI 95%*). In contrast, players in the tackler role saw statistically significant differences between head contact height and contact at the shoulder (*p = 0.031, α = 0.05, CI 95%*), chest (*p=0.014, α = 0.05, CI 95%*), rib (*p = 0.009, α = 0.01, CI 99%*), hip (*p = 0.004, α = 0.01, CI 99%*), thigh (*p = 0.011, α = 0.05, CI 95%*), knee (*p = 0.006, α = 0.01, CI 99%*), and ankle (*p = 0.035, α = 0.05, CI 95%*). Tackler head contact tackles had a mean PAA magnitude of 6878.12rad/s^2 compared to the next closest tackle height when comparing magnitudes which was chest height at 5686.70rad/s^2. There were no other statistically significant differences in exposure to PAA for the tacklers between the other contact height classifications.

4.3.1.1 Tackle Video Analysis

As highlighted in the previous section, tackle PLA and PAA magnitude can vary due to several factors including, but not limited to, contact height, tackle orientation, and role in the tackle. The above magnitudes tend to highlight that an increase contact height for either the ballcarrier or the tackler subsequently led to an increased experience of PLA or PAA. However, there were several events where the results were not as clear and only through consultation of video analysis does the impact of a particular factor become more apparent.

Part A. Black player (orange dot) on approach for a 1-on-1 tackle with red player (blue dot).

Part B. Black player (orange dot) performed a front below waist (FBW) tackle making contact with the thigh of red player (blue dot). The position of the black player's head was outside of the left leg of the red player with the point of contact for the black player being the left shoulder. Peak linear acceleration (11.43g) was reached at this point.

Part C. Black player (orange dot) slips off red player (blue dot) but still had one arm around the legs of red player. As red player continued moving forward, the black player was pulled round by the momentum of the red player. Peak angular acceleration was achieved at this point (12091 rad/s^2).

Figure 4.8. *Video analysis of a front below waist (FBW) 1-on-1 tackle with relatively low linear magnitude but high (for a front tackle as a tackle) angular acceleration magnitude.*

In the example laid out in fig 4.8., the tackler experienced a relatively low linear head acceleration but high angular acceleration during an event which has previously been highlighted to have high PLA and moderate PAA. The tackler made contact with the ballcarrier's legs and kept his own head away from any direct contact, which could explain the lack of high exposure to PLA. However, later in the event, the tackler was dragged around by the momentum of the ballcarrier potentially resulting in an increase in angular acceleration for the tackler.

Part A. Ballcarrier (orange dot) running a “hard line” close to 5m line of opposition half. Blue dot players are the future tacklers.

Part B. Tackling players (blue dots) make contact with the ballcarrier (orange dot). Both tackling players make contact between the chest and ribs of the ballcarrier with their shoulders. There was no head contact. At this point, peak linear and peak angular acceleration for this HAE were reached simultaneously (PLA = 26.86g, PAA = 29878 rad/s^2).

Part C. Ballcarrier is bounced off the two tacklers (head of second tackler obscured from view) and brought to the floor in a following frame. Ballcarrier was clearly dazed and was removed for an HIA but later returned to the pitch.

Figure 4.9. *Video analysis of high PLA and PAA experienced by ballcarrier during double tackle event.*

In contrast to fig. 4.8., fig. 4.9. highlighted a tackle event where contact was made to the ballcarrier between the chest and ribs by two tacklers. The ballcarrier experienced high PLA and PAA during this contact event. This could potentially suggest that another confounding factor could be contributing to head acceleration experience.

4.3.1.2. Discussion - Tackle Magnitude and Video Analysis

To summarise what has been described regarding tackle events; tacklers have a higher exposure to PLA, whereas ballcarriers have a higher exposure to PAA. The maximum PLA threshold was achieved only during front orientated tackler events where the contact height was at the head, shoulder and hip. The maximum PAA threshold was achieved during a ballcarrier double tackle and a tackler behind orientated tackle. The behind tackle was identified during the video analysis and the reviewer highlighted that the foot of the ballcarrier kicked the tackler in the head potentially explaining this outlier event. The magnitude data also highlighted that there are potentially some tackle orientations and heights that result in increased exposure to PLA and PAA, however, there is evidence throughout the video analysis that occasionally disputes this. The statistical analysis of tackle orientation indicated that a behind tackle, or more colloquially a covering tackle, could be preferable to limit player exposure to PLA and PAA, for both ballcarrier and tackler. Ballcarrier and tackler PAA did not differ significantly between front and side orientated tackles. The PLA exposure of ballcarrier and tackler during front and side tackles was significantly higher for the tackler. There was no significant difference between PLA exposure during behind and double tackles between ballcarrier and tackler, however, there was significantly more exposure to PAA for ballcarriers during behind tackles, but this observation was not repeated during double tackle events. The contact height of the tackle resulted in significantly greater PLA and PAA when contact was made to the head or neck of the ballcarrier. Somewhat unexpectedly, varying the contact height only produced significantly different PLA exposure for the ballcarrier not the tackler even though, as previously highlighted, PLA is traditionally higher for the tackler. For the ballcarrier, significant differences in PLA between direct head contact and contact to other parts of the body were observed ($p \leq 0.01$). The only other significant differences for ballcarriers concerning contact height occurred when tackle contact height was at shoulder height which resulted in higher PLA than tackles with contact at the rib, hip or thigh ($p < 0.05$). For the tackler, there was no significant change in PLA when the tackle contact height was increased or decreased. However, when tackle contact was at the head the PAA was significantly higher than all other contact height classifications ($p \leq 0.05$) with notably higher PAA between head contact and any of the below waist classifications ($p \leq 0.001$). This data suggested that if the players increase the contact height this resulted in significantly higher PAA exposure for ballcarriers and significantly higher PLA in tacklers.

Therefore, taking in to account the tackle orientation, role and height data, it could be suggested that to limit exposure to linear and angular acceleration, in an ideal and potentially hypothetic environment, players should aim to make below waist, behind or side tackles involving only one ballcarrier and one tackler. Ballcarriers should look to protect themselves from excess exposure to higher PLA and PAA by not increasing tackle height and remaining as upright as possible during contact. In addition, ball carrying players should look for opportunities to avoid running directly at opposing players which subsequently forces their opponent into making a front or double front tackle, ultimately resulting in higher head acceleration exposure for the ballcarrier. The practicalities of these recommendations would require further research and discussion with appropriate governing bodies to implement. Nevertheless, if players can be aware of the tackle types that can expose them to higher PLA and PAA, then when the game scenario allows, actively choose to make a different tackle type, for example, allow opposition gain line success and make a behind tackle, this may limit total PLA and PAA during the multiple tackle events completed during a game.

A finding that may also be of note, is the indication that the role of the player in the tackle influences the type of head acceleration that the player is exposed to. Depending on whether the reader supports the traditional mTBI research advocating for the risks associated with linear head acceleration (Brolinson et al., 2006; Guskiewicz and Mihalik, 2011; Rowson and Duma, 2013), or supports the more modern suggestions that cumulative angular acceleration is more damaging in neurodegenerative terms (Daneshvar et al., 2015; Oeur et al., 2014), will potentially alter the interpretation of these results. A wealth of research has been published (Stokes et al., 2021; Tierney et al., 2018; Tierney and Simms, 2017; Tucker et al., 2017) in support of lowering the tackle height to protect the ballcarrier, but does this just change the emphasis of the head acceleration exposure away from the ballcarrier and onto the tackler? In the results found in this study, there appeared to be limited statistically significant benefit in reducing tackle height below the shoulder. The area that highlighted clear, significant reductions in PLA and PAA exposure was tackle orientation, which was supported by video analysis, therefore, it could be suggested that this should be the focal area for future tackle research.

4.3.2. Ruck Magnitude: Types, Roles and Magnitudes

The ruck is another key contact area that has gained significant attention in published literature for contributing to head acceleration experienced by rugby players. Unlike the tackle, the ruck usually involves in excess of four players, not just a ballcarrier and a tackler.

The roles in a ruck can be largely separated into attacker, defender, guard, and floor. The potential for head acceleration exposure is evident in each of the roles and this section will look to highlight exactly where the PLA and PAA is most significant. Different techniques utilised at rucks can also result in players adopting different body positions which could also alter exposure to head acceleration.

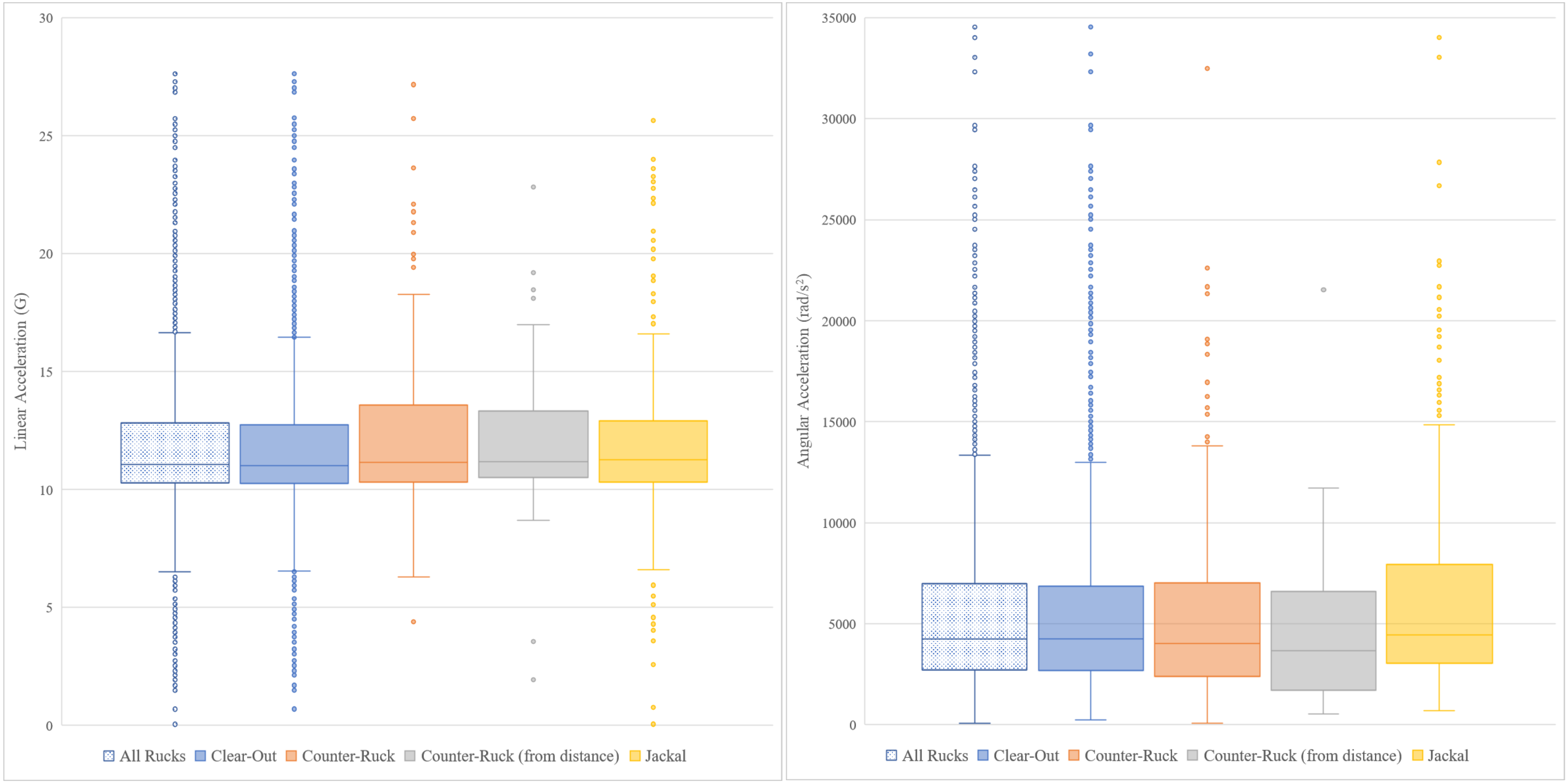

Figure 4.10. *Distribution of peak linear (PLA) and peak angular head acceleration (PLA) of ruck event micro classifications*[7].

[7] Micro (fig. 4.10.) and nano (fig. 4.11.) ruck classifications are described and defined in Chapter 2..

The micro classifications of rucks all had relatively similar median and IQR PLA values (CO = 11.15g (2.76), CR = 11.34g (3.61), CRD = 11.18g (2.82), JCK = 11.26g (2.77). Counter-ruck (CR) events had the highest median and highest IQR suggesting that this event type resulted in a variable experience of linear head acceleration for players. CR events also had higher 75th percentile PLA than all other ruck event types and a lower 25th percentile than the other ruck types with the exception of counter-ruck from distance events. Jackal (JCK) ruck events and counter-ruck from distance (CRD) events had very similar levels of variability, however, the CRD events had higher 25th and 75th percentile values. Maximum PLA threshold was only achieved during a clear-out ruck type. This result was considered an outlier for all rucks.

Fig. 4.8. indicates slightly more variation in PAA than PLA during ruck events across the four micro classifications. Similar median PAA values were observed between all ruck types (CO = 4238.13rad/s^2 (4170.03), CR = 4022.33rad/s^2 (4646.30), CRD = 3665.09rad/s^2 (4912.73), JCK = 4452.3rad/s^2 (4881.9)) with CRD rucks having the lowest PAA median value of all ruck types. The three ruck types with significant event frequency all have similar PAA variability with observably higher 25th and 75th percentiles during JCK rucks. Maximum PAA threshold was almost achieved during a CO ruck (34605.81rad/s^2) and during a JCK ruck (34021.64rad/s^2).

Mann Whitney-U tests were used to conduct a series of pairwise comparisons of the different PLA and PAA exposure for players during the four ruck micro classifications. None of the differences observed regarding variation in PLA were considered significant ($p > 0.05$, *CI 95%).* Statistically significant differences in PAA were observed between CO-JCK ($p \leq 0.001$, *CI 95%*), CR-JCK ($p = 0.015$, *CI 95%*) and CRD-JCK ($p = 0.018$, *CI 95%*). The differences in PAA between CO-CR ($p = 0.329$, *CI 95%*), CO-CRD ($p = 0.175$, *CI 95%*) and CR-CRD ($p = 0.46$, *CI 95%*) were not considered significant. It would also be necessary to acknowledge the large difference in ruck type frequency (Table 4.4.) which could potentially result in spurious statistical test outcomes concerning CRD rucks.

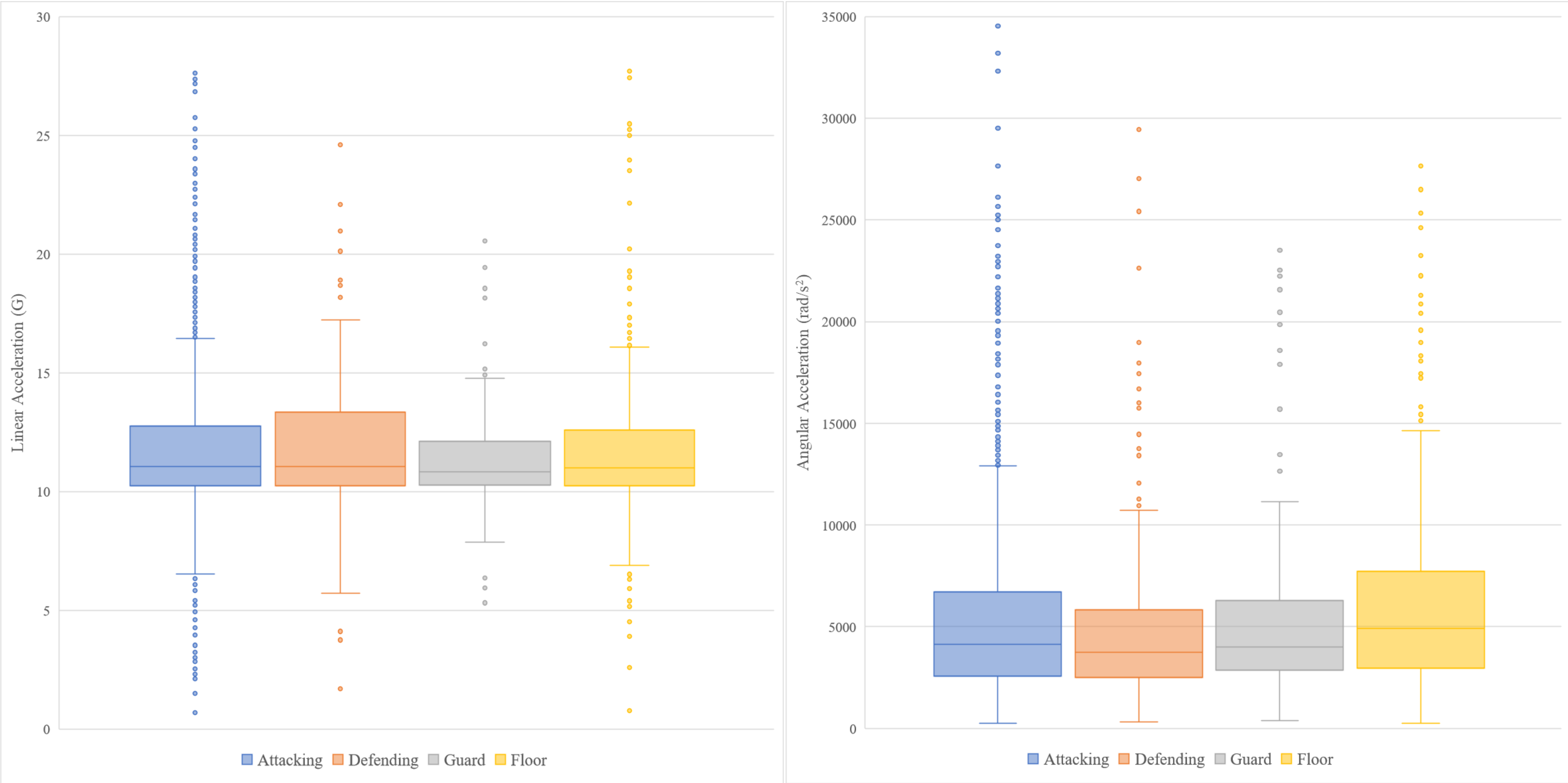

Figure 4.11. *Distribution of peak linear (PLA) and peak angular head acceleration (PAA) of nano classifications (roles) during ruck events.*

Figure 4.9. highlights the variation in PLA and PAA experienced by players performing different roles in ruck events. Attacking and defending players were categorised as players actively competing at the ruck from the attacking and defending teams, respectively. Guard players were players who were bound to the ruck, but not taking part in competing for the ball, and could be from either attacking or defending teams. Players designated as "floor" were players that were off-their-feet at the ruck, either due to being part of the original tackle event that resulted in the ruck or being taken to the floor as a result of competitive action at the ruck. Unlike tackles, ruck events could last for several seconds, where there was the possibility for a player to experience multiple HAEs resulting in separate ITU triggers. Therefore, players' roles could change throughout the duration of the same ruck.

When organised by role in the ruck, PLA medians are separated by 0.08g (Attacker = 11.05g (2.5), Defender = 11.07g (3.1), Guard = 10.83g (1.81), Floor = 11.01g (2.34)) with relatively similar levels of variability. There were no statistically significant differences observed between any of the ruck roles concerning PLA. Maximum linear acceleration ITU threshold was achieved by a player on the floor with an attacking player also close to achieving PLA threshold. PAA medians were separated by a range of 1173.4 rad/s^2 and high levels of variability were observed across all ruck roles. (Attacker = 4124.19 rad/s^2 (4143.0), Defender = 3753.75 rad/s^2 (3325.14), Guard = 4011.71 rad/s^2 (3430.35), Floor = 4927.15 rad/s^2 (4756.21)). This data suggests that the greatest exposure to PAA usually occurred after players have finished competing for the ball and are no longer in control of their body movement due to being off their feet. The differences between attacking, defending and guard players, in terms of PAA, were not considered significant. In contrast, the differences between attacking and defending, and floor players were considered statistically significant (ATT-FLO: $p < 0.001$ *CI 95%;* DEF-FLO: $p = 0.003$, *CI 95%*). Maximum angular acceleration threshold was only achieved by an attacking player. No other ruck roles were within 2000 rad/s^2 of maximum threshold.

4.3.2.1. Ruck Video Analysis

The magnitude data tends to portray a mixed picture of head acceleration exposure for each ruck type and for the roles within ruck events. A common theme was the suggestion that the jackal ruck for a defensive player can result in high head acceleration magnitude. In fig. 4.12., the defending player starts is the first defending player to the event and attempts to jackal.

Part A. Defending player (#7 Black) in ruck supporting own body weight intially attempting to jackal then hands off. At this point, ITU signal recording begins.

Part B. Attacking players (#14 Blue (blue dot) and #8 Blue) attempt CO style ruck of Black #7 (orange dot). At the point where the head of Blue #14 makes contact with the head of Black #7 peak linear acceleration (16g) for the event was achieved. 29ms later peak angular acceleration (8823 rad/s^2) was achieved.

Part C. Black #7 (orange dot) is "cleared out" from the ruck and falls to the ground.

Figure 4.12. *Video analysis of a clearout ruck event with medium magnitude of linear and angular head acceleration for a defending player where direct head contact occurred.*

The player's experience of PLA and PAA varies throughout the ruck event, with a slight staggering observed between peak acceleration in linear and angular motions. The notable feature about this particular event is that it contained direct head-on-head contact between Black #7 and Blue #14, however, Black #7's experience of head acceleration was relatively minimal when compared to some of the head-on-head contact PLA and PAA values seen during other contact events. Data does not exist for Blue #14 as he was not part of the study. This was also somewhat of an isolated event; direct head contact during rucks almost always triggered a high PLA and/or a high PAA.

Part A. Attacking player #8 (orange dot) and attacking player #7 (yellow dot) approached the tackle area to attempt to clearout defending player #2 (blue dot).

Part B. Attacking player #8 (orange dot) and defending player #2 (blue dot) both go low into the ruck and make head to head contact. Attacking player #7 (yellow dot) makes contact with his shoulder into the ribs of the defending player. PLA for orange dot reached maximum ITU threshold, whereas PLA for yellow dot was 12.18g. PAA for orange dot was 22981 rad/s^2, whereas PAA for yellow dot was 16541 rad/s^2.

Part C. Both defending and attacking players are now non-competing as they have left their feet. There is residual head acceleration for both attacking players at this point.

Figure 4.13. *Video analysis of two attacking players performing a clear-out style ruck with varying experience of PLA and PAA head acceleration.*

Both attacking players performed the same role, but their experience of the event was totally different when looking at PLA and PAA. Black #8 leading with the head and making contact directly with the head of the defending player potentially exacerbated the experience of the HAE. Both attacking players also accelerated into the ruck which may have also been an extenuating factor when considering experience of head acceleration magnitude.

4.3.2.2. Discussion - Ruck Magnitude and Video Analysis

The different ruck types provided mixed results regarding player head acceleration experience. Clear-out style rucks were the most frequent type of ruck, followed by counter-rucks and then jackal type rucks. The difference in PLA during clear-out, counter-ruck and jackal type rucks was not seen as statistically significant following a Friedman's test (*p = 0.078, 95% CI*). In contrast, the PAA experienced during clear-out and counter-ruck type rucks was statistically significantly lower than experienced during jackal rucks ($p < 0.001$, *95%*). Statistically significant differences in PAA were observed between clear-out and jackal rucks ($p \leq 0.001$, *CI 95%*), counter-ruck and jackal rucks ($p = 0.015$, *CI 95%*), and between jackal and counter-ruck from distance rucks ($p = 0.018$, *CI 95%*). There was also large variation in PAA across all ruck types, whereas PLA was relatively consistent except for during counter-ruck events which had a notably larger IQR.

Clear-out type rucks dominate the frequency landscape of ruck types. This ruck type appeared to be the easier to perform under fatigue and required the lowest level of technique or physical strength. This was identified during the video analysis stage indicating a propensity for a reduction in counter-rucks towards the end of each match. Also identified during the video analysis stage, were distinct mechanical differences existing between the clear-out rucks and other ruck types. For example, during a clear-out style ruck, the defending player was often stationary over the ball and players attempting to either get hands on the ball where the ruck would become a jackal type, or clear opposition floor players out. The attacking players would then arrive at speed and use momentum generated by running and make contact with defending players. The difference in PLA and PAA experienced between attacking and defending players was not seen as statistically significant. However, this could be a reflection of after initial contact, if defending player remains in situ, the players largely perform similar roles. This theory relies heavily on the idea of an almost linear transfer of energy between attacker and defender to result in an ITU trigger but when individual events are compared, such as in Chapter 3, there appeared to be attacker trigger followed by a delay of between 0.07 - 0.15s before the defender trigger. It could also be argued that there are some similarities between clear-out rucks and counter-rucks after the initial contact phase. A clear-out would consider the attacking player as controlling the contact area, whereas the counter-ruck places the onus of control of the contact area on the defender. Therefore, these two ruck types are similar but with the labelling of the roles reversed.

There was not a high enough frequency of counter-rucks from distance to assess any differences with a significant level of confidence. Further research into the ruck area with a greater focus on the approach of players to the ruck could potentially outline how the initial contact affects the experience of linear and angular head acceleration.

Jackal rucks for the defending player are very technical and difficult to successfully gain control of the ball when compared with counter-rucks (Wheeler et al., 2013). As previously mentioned, jackal rucks are similar in terms of PLA when compared to other ruck types but have significantly higher PAA. The higher PAA during jackal rucks is a phenomenon that requires some investigation. During a jackal, the defensive player places their hands on the ball carried by a tackled player to attempt to gain possession or a penalty. By placing their hands on the ball, defending players often lower their heads towards the ground, leaving limited space between their head and remainder of their body for an attacking player to perform a clear-out ruck. Although, a common means for gaining possession or a penalty, this body position could potentially be exposing defensive players to a high risk of experiencing an increased magnitude of angular acceleration. The defensive player often does not see the attacking player prior to contact and so has limited time to protect themselves before the impact. As alluded to during the discussions around the tackle events, a player that is not in control of initiating the contact event often has little control over their exposure to head acceleration subsequently resulting in an increase in PAA. Ultimately, the main finding from the ruck event results suggests that the player who is in motion dictates the head acceleration outcomes. For example, the head of the defender during jackal rucks is exposed and so this leads to a higher magnitude of PAA. Alternatively, the statistical similarities observed in PLA and PAA between clear-out and counter-rucks with the higher magnitude in PLA usually attributed to the stationary player (defender during CR, attacker during CO).

4.3.3. Other Contact Events: Lineout, Scrum & Maul

Tackle and rucks resulted in over 50% of all contact events included within this study. However, there is significant evidence to suggest that other contact event types also contribute to head acceleration exposure during rugby union matches (Ravin et al., 2022; West et al., 2022). Scrums have been traditionally associated with neck and spinal injuries more than mTBI (Trewartha et al., 2015) with research from late 20th century (Wetzler et al., 1998) up until present studies placing emphasis on the inevitable issues to the cervical and in some cases, thoracic portions of the spine (Roberts et al., 2015). Risk of mTBI is usually suggested to be low for all players during scrums, but particularly for second and back row players with the main risk attributed to engagement for front row players. Lineouts have the propensity for moderate velocity collisions particularly for the jumper and lifting players. Competition in the air between lifted players and the sometimes, uncontrolled descent of the lifted players can result in notable head acceleration events. Lineouts regularly conclude in a maul which is considered an essential dynamic part of the game. However, due to the number of players involved and lack of control when binding, the upright body position of some players, and the proximity of the players, head acceleration events are somewhat inevitable. Of all rugby union contact events, lineouts, mauls and scrums continue to avoid the intense research focus that the tackle has received. However, the data displayed in this chapter suggests that notable head acceleration magnitudes occurred during these contact events.

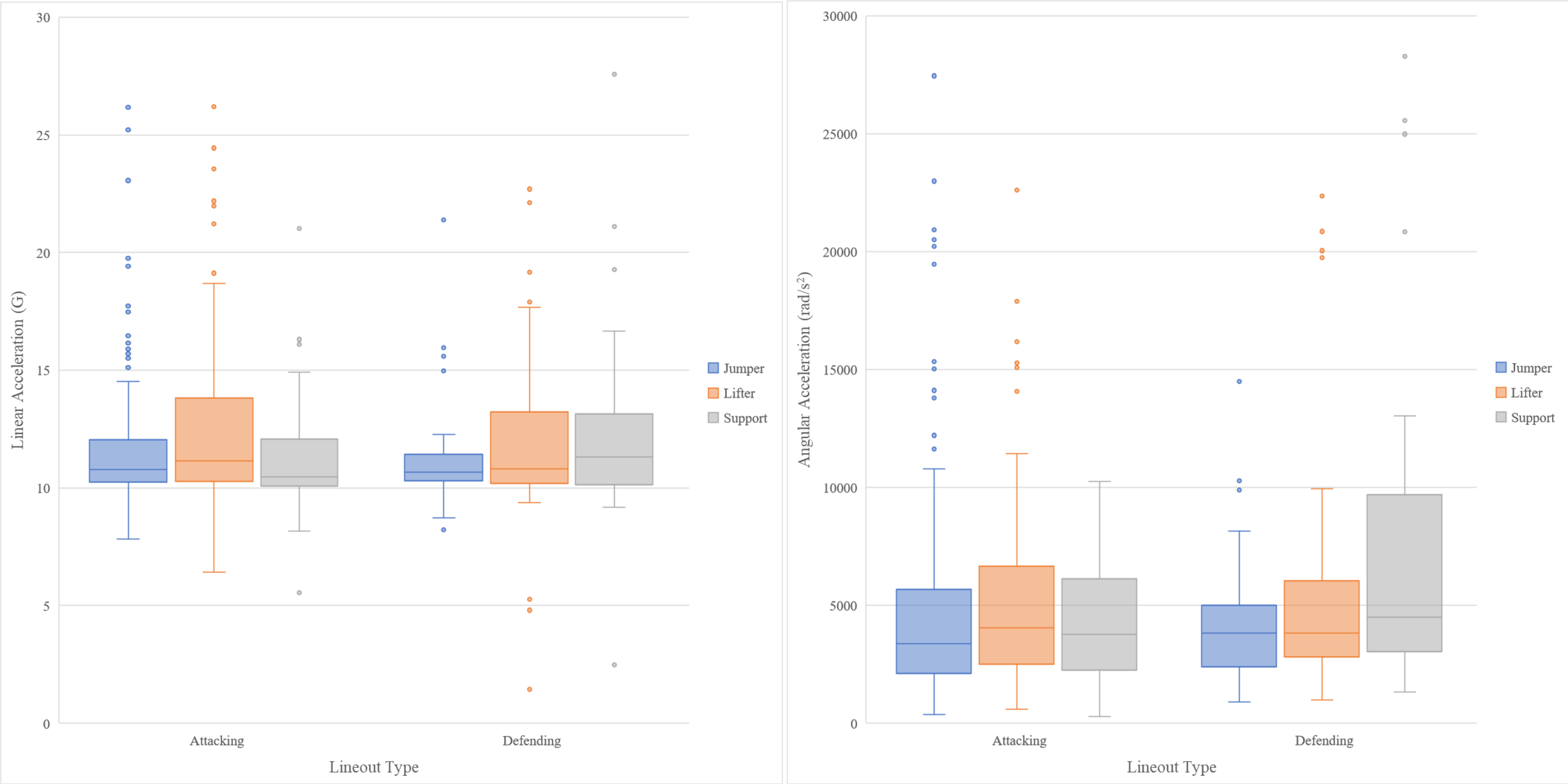

Figure 4.14. *Distribution of linear and angular head acceleration during lineout events represented by attacking and defensive types and player roles.*

During attacking lineouts, the lifting players experienced the highest median PLA and PAA but also much greater variability than the other roles in the lineout. In contrast, median PLA and PAA was greatest for support players during defensive lineout events.

The variability of PLA experienced by jumpers appeared to be greatest whilst attacking rather than defending. Median PLA was similar throughout, and differences observed across the jumper sample were not considered significant (*p = 0.22 CI 95%*). Lifting players observed greater variability in PLA than jumpers and support players when attacking but similar variability in PLA was observed between attacking jumpers and support players. Lifting players had the higher median PLA during attacking events. In contrast, support players had the highest median PLA during the defending events. The maximum PLA experienced during lineout events was by a support player during a defensive lineout.

The variability in attacking PAA was similar between all attacking lineout roles. However, the variability in PAA was significantly higher for support players who were defending during the lineouts. Maximum PAA recorded during lineouts was also achieved by a defending support player. Median PAA for jumpers and lifters when attacking and defending was relatively similar, and no significant differences were identified between the groups (attacking: *p = 0.381 CI 95%*; defending: *p = 0.128 CI 95%*). In contrast, the difference in PAA experienced by attacking and defending support players was considered statistically significant (*p = 0.041 CI 95%*). As further indication of the higher PAA experienced by support players, during defensive lineouts, 75^{th} percentile PAA for support players is only 1352 rad/s^2 less than maximum PAA value (non-outlier) for lifting players.

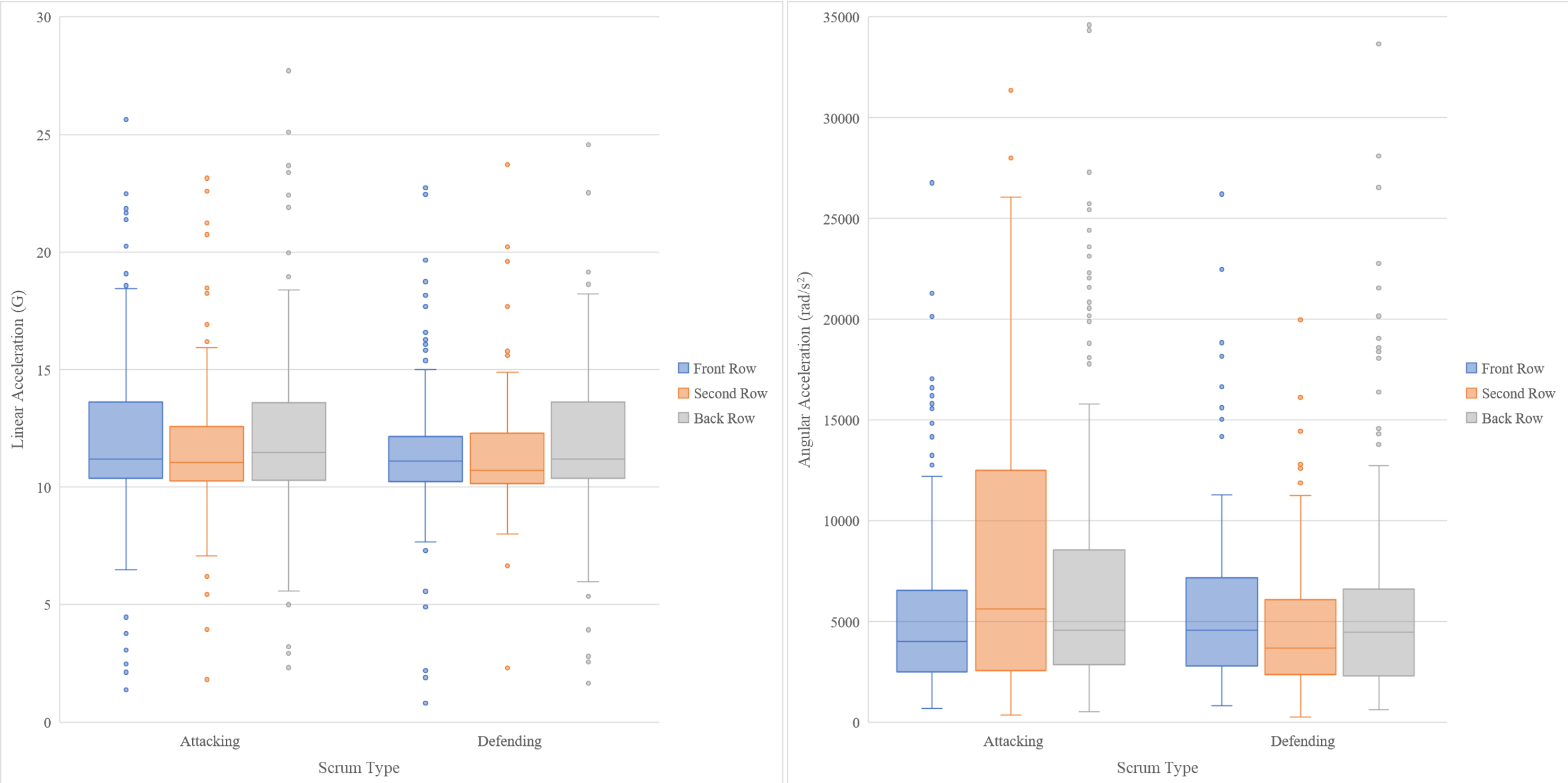

Figure 4.15. *Distribution of linear and angular head acceleration during scrum events represented by attacking and defensive types and player roles.*

The PLA experienced by players during attacking and defending scrums was not considered statistically significantly different (*p = 0.391 CI 95%*). However, there were observable differences in PLA exposure between different player roles during attacking and defending scrum events. For example, median PLA remained similar for front row players during both scrum types. No statistically significant differences were observed (*p = 0.116 CI 95%*) but there was an increase in variability in PLA experienced by front row players during attacking scrums. Maximum PLA for front row players was relatively low (25.6g) compared to the other player scrum roles and when evaluated against the maximum PLA magnitude of other contact events. PLA experienced during attacking and defending scrums for second row players was almost identical in terms of median PLA and IQR. No statistically significant difference was found between second row player exposure to linear acceleration (*p = 0.643 CI 95%*) during attacking and defending scrums. In contrast, back row exposure to PLA was observed to be statistically higher during attacking scrums (*p = 0.044 CI 95%*). Variability of exposure to PLA was similar for back rows during both scrum types.

PAA exposure was notably higher during attacking scrums (*p = 0.039 CI 95%*), however, median PAA for front and back row players was higher during defensive scrums. The most notable feature concerning PAA exposure was the large range, and IQR, of angular acceleration experienced by second row players during attacking scrum events in contrast to the relatively small variability of PAA experienced during defensive scrums. Overall, PAA variability was higher for all players during attacking scrums, in addition to the maximum recorded PAA exposure during a scrum event occurring during an attacking scrum. As with PLA, the maximum PAA was experienced by a back row player potentially suggesting an association between back row players, scrums and peak head acceleration magnitudes. Statistically significant differences concerning player role experience of PAA during scrum events was only found between attacking and defending second row players ($p < 0.001$ *CI 95%*).

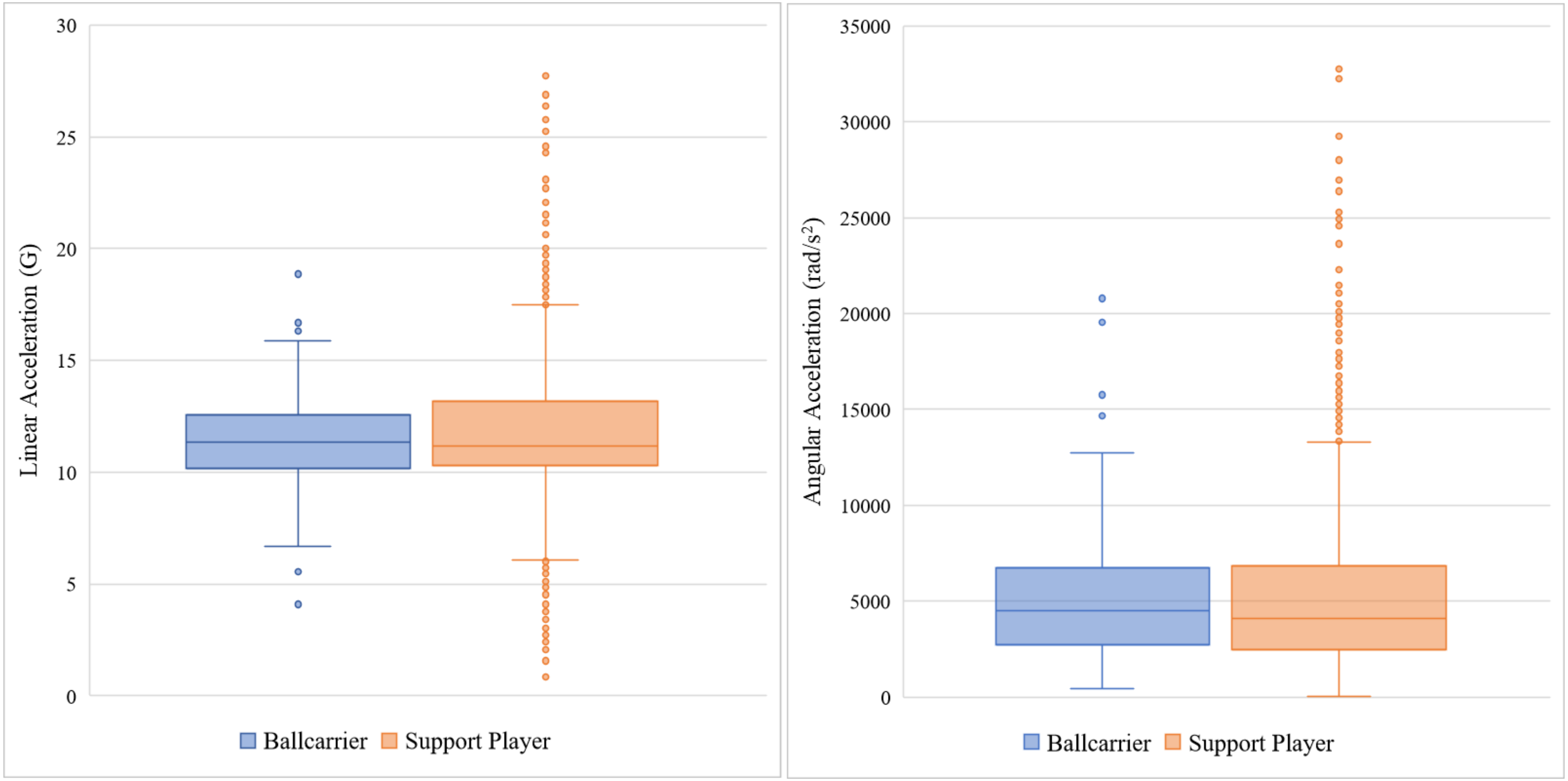

Figure 4.16. *Distribution of linear and angular head acceleration during maul events represented by player roles.*

PLA during maul events was limited in its variability with ballcarrier exposure to linear acceleration IQR at 2.24g and support player IQR at 2.86g. Median PLA during mauls was slightly higher than support player median PLA, but this difference was not considered statistically significant (*p = 0.467 CI 95%*). Although the IQR values for ballcarriers and support players were similar, there were far more outlier results for support players including the maximum recorded linear acceleration of 27.71g, in contrast with ballcarrier maximum PLA of 18.86g. PAA exposure indicated similar trends to PLA exposure during maul events including slightly higher, but not significantly so, PAA for ballcarriers but a higher variability of PAA for support players.

It is necessary to note regarding the maul HAEs that the sample of ballcarrier events was far smaller than the sample of support player events. Due to the variation in sample size, all statistics were computed using alternate statistical tests where mitigation for unequal variance could be applied. For example, in the case of two parametrically distributed variables with unequal variance, Welch's *t*-test was used. Welch's *t*-test, and non-parametric equivalents, increase the test's degrees of freedom, in contrast with an independent *t*-test, allowing for an increase in statistical power.

Head acceleration exposure during maul events is a notably under-researched area and the sample of HAEs contained in this study is only a small addition to this underdeveloped research field. Combining the frequency and magnitude data highlights the contribution of maul events to the cumulative head acceleration load experienced during rugby union matches. Further research needs to be conducted to completely understand the player experience of head acceleration during maul events.

4.4. Summary

Tackles and rucks accounted for 57.9% of all validated contact events during this study. The tackle results in more ITU triggers than the ruck. The frequency of the other contact events varies by match. There are several matches with a high frequency of collisions, similar to that of tackles and rucks, which have a relatively small volume of research regarding HAEs. Non-specified event collisions are still understudied in terms of their contribution to overall head acceleration load and several published papers do not differentiate between designated events and non-specified collisions (Reardon et al., 2017; Roe et al., 2016). This lack of specificity has made it quite challenging to compare to previous literature. No published papers make reference in terms of non-specified collision magnitude, however, similar tackle counts and ruck counts have been observed in other studies (Quarrie et al., 2013; Quarrie et al., 2017; Rafferty et al., 2019). Further published research has suggested that the magnitude of HAEs observed in this study align from a linear acceleration perspective. In contrast, in almost all of the contact events, higher angular acceleration has been observed in this study.

During tackle events, tacklers appeared to be exposed to higher PLA whereas ballcarriers were exposed to higher PAA. In terms of tackler orientation, front and side tacklers resulted in higher PLA for the tackler and increased PAA for the ballcarrier. However, maximum PLA was achieved by a ballcarrier during a front orientated tackle due to the contact being directly with the head. There is significant evidence to suggest that exposure to both PLA and PAA is increased when contact is made directly with the head of either the tackler or the ballcarrier. There is no statistical evidence to suggest lowering the tackle contact height below the shoulder results in any significant reduction in head acceleration magnitude. Throughout majority of tackle events, PAA was higher for the ballcarrier which could potentially be a resultant factor of an uncontrolled collision. Behind orientated tackles had the lowest PLA and PAA of all tackle orientations with the occasional outlier result, suggesting that a non-dominant or covering tackle may be beneficial in reducing exposure to head acceleration.

Clear-out ruck types were the most frequent ruck type observed during the research period. This suggested that a clear-out ruck can be completed throughout the match whilst under fatigue. In contrast, the jackal is considered a more technical ruck type and so is inaccessible to some players, whereas the counter rucks require significantly more energy to complete and were rarely observed during the fourth quarter of matches. No statistically significant differences were observed regarding PLA between any of the ruck types. There was large variation in PAA experienced by players during ruck events. PAA exposure during jackal ruck types was considered statistically higher than clear-out and counter ruck events. No statistically significant differences were observed between clear-out rucks and counter rucks but the idea was proposed that from the video analysis, these rucks appeared almost identical in terms of mechanics. During clear-outs, attacking players controlled and initiated contact, whereas the defending player controlled the contact during counter rucks. The idea of which player controls the contact and whether this has any influence on experience of head acceleration requires further research.

Mauls, lineouts and scrums all contributed to the cumulative head acceleration load experienced by players during matches. During attacking lineouts, lifting players tended to have the highest exposure to PLA and PAA. Support players also had notable exposure to PAA but there was also high variability in the PAA experienced by support players potentially due to the variation in classification of support player. For example, players in the lineout but not actively participating in lifting or jumping could be over two metres away from where the competition for the ball is occurring, developing into slight results distortion. During scrums, second row players had the lowest median PLA but the highest median PAA during attacking scrums. Experience of PAA for second rows during defensive scrums was the lowest out of the three player groups. Front row players experienced relatively minimal head acceleration during attacking scrums but appeared to have increased head acceleration magnitudes during defensive scrums. The maximum recorded PAA was by a back row player during a defensive scrum. In addition to this, back row experience of PAA was notably more varied than other player groups. In contrast still, variability in PAA was highest for second row players during attacking scrums.

Other general themes included a distinct lack of differences in PLA between contact events, player roles, orientations and heights. For statistically significant test results concerning PLA very specific grouping was required to indicate a significant result. On occasion where large samples of contact events were used, events that had previously been considered mechanically different appeared to be almost identical. For example, previous evidence suggesting that a reduction in tackle height protects both ballcarrier and tackler (Tucker et al., 2017), whereas in contrast, results from this study indicate that that conclusion is too vague and requires specific action to from both tackler and ballcarrier to result in lower magnitudes of head acceleration. Statistically, this could be due to the obtrusively large sample sizes distorting statistical tests, but it also could be a reflection of the low sampling hertz of the ITUs resulting in a lack of sensitivity or potentially a reference to the difference between a statistical difference and real-world differences.

A significant finding of this chapter proposes the argument of control in the contact event. The player initiating the contact is often considered the player in control of the contact event, for example, the tackler is the main controller of contact height in the tackle as the ballcarrier can only reduce their body height a small amount whilst carrying the ball. Some of the data throughout this chapter has suggested that the player with less contact control has an increased chance of higher head acceleration. However, there are also arguments suggesting that both players experienced similar head acceleration magnitudes but at different times during the contact event in this chapter. Arguments indicating that the player 'in-control' of the contact, for example, the tackler can experience lower median PAA, however, in the initial phase of the contact, tackler often experience higher magnitudes of PLA. Throughout the chapter, suggestions have been made that the player, or players that initiate the contact are often the individuals that dictate the magnitude of the HAE. During the lineout, scrum and maul, where the initiation of contact is more even, there is less of a distinction between attacking and defending players.

Ultimately, depending on whether the reader considers linear acceleration or angular acceleration as more dangerous to brain health could potentially dictate an interpretation of which events and roles, and orientations could be considered higher risk when reflecting on accumulation of subconcussive head accelerations.

4.5. Link to next chapters

To fully understand the effects of multiple head acceleration events, it is important to identify the differences across the two seasons from a temporal standpoint, but also with a view of the potential differences that could occur due to variation in opponent competency level across the two tiers. Identification of high magnitude roles and positions could also be beneficial to improve the management of certain players. This chapter has alluded to ideas of different player groups and player roles have an impact on a player's experience of head acceleration during a contact event. Further clarity is required to assess which players may be at an increased risk of high cumulative load across multiple matches, training sessions and seasons. The cumulative loading element of this debate is discussed further in Chapter 7.

Chapter 5

A comparative analysis of head acceleration events (HAEs) in tier 1 and tier 2 of English professional men's rugby union.

"*As an international federation and Olympic sport, World Rugby recognises this power of sport to act as a catalyst for peace and societal development. Along with the global rugby family, we have a shared responsibility to use rugby to improve lives and communities.*"

- Spirit of Rugby: Sport as a tool for good, World Rugby, July 2015.

Chapter 5 - List of Tables and Figures

Figure 5.3. *Median PAA during different contact and non-contact events that resulted in an ITU trigger during Premiership matches.*

Figure 5.4. *Median PAA during different contact and non-contact events that resulted in an ITU trigger during Championship matches.*

5.1. Introduction

England is the one of only two countries in Europe with two tiers of fully professional men's rugby union teams, the other being France, which are supported by several tiers of semi-professional teams (Harris, 2010). The variation in magnitude and frequency of head acceleration events in two separate, but professional tiers of rugby union is yet to be explored in any capacity, at the time of writing. As alluded to in Chapter 1, there is significant work suggesting that an increase in player ability level, results in an increase injury risk (Viviers et al., 2018). Therefore, it could be hypothesized that due to the increased size and physicality of tier one rugby union players and in line with published research suggesting that tier one results in the highest injury burden (Robertson et al., 2022), contact events experienced during the Premiership matches could be of a higher magnitude and higher frequency that those experienced during Championship fixtures. However, allowing simplistic assumptions implying a linear relationship between player size and head acceleration exposure without consideration of multiple confounding variables could lead to misappropriation of head acceleration data. Currently, the largest body evidence for predicting mTBI likelihood uses individuals that have sustained repetitive mTBI events, indicating that possibility of mTBI is increased exponentially after first mTBI experience (Moore et al., 2023).

Associations can be made between different tiers of rugby union by comparing elite and community formats (Gardner et al., 2014). However, there are suggestions that vast differences exist between the physiological demands of each level of the game (Roberts et al., 2008; Read et al., 2017a) which could result in the opinion that differences in magnitude and frequency of HAEs should be expected. In age grade rugby, where similar physiological discrepancies exist, there is limited experience of HAE consistency between grades; Bussey et al. (2023) suggest that U13 players are at lower risk when compared to U15 and U19 age group, and Premiership players. However, no significant differences in magnitude were observed between U15, U19 and Premiership players.

There is a necessity to outline the differences in magnitude of contact events experienced at different tiers of the English professional rugby union pyramid and to propose some ideas as to the reasons behind cross-season variation and variation between players participating in identical contact events occurring a season apart. The data presented in this chapter highlight the differences in contact event frequency and magnitude experienced during tier one (Premiership) and tier two (Championship) matches.

5.2. Protocol

Two seasons of head acceleration event data was collected with a professional rugby union team over two tiers of English domestic rugby; the Gallagher Premiership (hereinafter referred to as “the Premiership”) and the Greene King IPA Championship (hereinafter referred to as “the Championship”). The same professional rugby union team was used for both seasons and the player roster remained largely unchanged between each season. Ten matches were recorded during each season and all matches were played at the same ground on an artificial surface (3G).

The ITUs (Protxx Inc.), setup protocol and monitoring software was identical to the descriptions in Chapter 3 and Chapter 4. Data was analysed using a combination of SPSS, R programming and Microsoft Excel to run statistical tests and create visualisations.

5.3. Results

5.3.1. Inter-Season Contact Event Frequency

Table 5.1. *Gross contact event frequency for Championship and Premiership matches.*

Contact Event	Tackle	Ruck	Scrum	Maul	Lineout	Collision	Total
Premiership	1798	1502	296	712	207	965	5660
Championship	1974	1296	581	521	255	1247	5874

Table 5.2. *Per player per match contact event frequency for Championship and Premiership matches*.

Contact Event	Tackle	Ruck	Scrum	Maul	Lineout	Collision	Total
Premiership	13.19	9.69	3.48	4.75	2.44	6.43	39.97
Championship	13.16	8.64	6.84	3.47	3.00	8.31	43.42

Gross contact event frequency indicated more contact events occurring during the Championship season than in the Premiership season. The per player per match frequency outlined how more tackle and ruck events resulting in ITU triggers occurred during the Premiership season but ITU triggers whilst players were involved in scrum, maul, lineout and collision events were more common in the Championship. Overall, the relative contact event frequency per player was higher in the Championship.

Table 5.3. *Median peak linear and angular acceleration (IQR) for Championship and Premiership matches.*

Match	Median Peak Linear Acceleration (IQR) (g)	Median Peak Angular Acceleration (IQR) (rad/s^2)
C01	11.14 (0.85)	4338.42 (2098.63)
C02	10.42 (0.35)	3984.42 (823.97)
C03	10.91 (0.45)	3863.45 (578.84)
C04	10.85 (0.27)	3567.11 (511.31)
C05	10.85 (0.31)	3712.54 (948.80)
C06	11.39 (0.98)	3633.78 (1024.55)
C07	10.99 (0.45)	4918.06 (1674.78)
C08	10.83 (1.01)	5010.55 (2022.53)
C09	10.98 (0.65)	3249.33 (1382.84)
C10	11.03 (0.62)	4688.57 (393.09)
C-Season	10.94 (0.61)	4096.62 (986.68)
P01	11.59 (1.34)	6910.60 (3037.16)
P02	11.19 (0.33)	3999.67 (613.34)
P03	11.07 (0.59)	3914.94 (699.56)
P04	11.54 (0.68)	4049.67 (739.57)
P05	12.31 (1.71)	5101.97 (1409.75)
P06	11.81 (0.59)	4144.61 (898.80)
P07	11.03 (0.44)	4663.76 (1803.10)
P08	11.51 (0.69)	4416.96 (387.59)
P09	11.37 (0.83)	3994.22 (368.52)
P10	11.97 (1.23)	6457.43 (2984.13)
P-Season	11.54 (0.85)	4765.38 (819.19)

Games are listed chronologically. “C” followed by a number indicates a Championship game “P” followed by a number indicates a premiership game. P-season or C-season represents a summary result for each season.

The Premiership season had a significantly higher PLA (*p = 0.013, CI 95%*) and PAA (*p = 0.039, CI 95%*) than the Championship season. Seven of the top ten games, ranked by magnitude of median PLA, were from the Premiership. The top ten exceptions from the Championship were C06 (7^{th}) and C01 (10^{th}). The lowest ranking Premiership game in terms of PLA magnitude was P07 (13^{th}). Six of the top ten games ranked by PAA, were from the Premiership with the Championship top ten exceptions being C08 (4^{th}), C07 (5^{th}), C10 (6^{th})

and C01 (9th). Even though C06 ranked highly in terms of PLA, the median PAA exposure during this game ranked 18th overall. Other games that had notable differences (defined as ranked difference > 10) between their median PLA and PAA ranks included: C05 (PLA_{RANK} = 18th, PAA_{RANK} = 3rd), C06 (PLA_{RANK} = 7th, PAA_{RANK} = 18th), and C08 (PLA_{RANK} = 19th, PAA_{RANK} = 4th).

Table 5.4. *Win-Loss (W/L) outcomes of matches from each tier.*

	Result	
Game Number	Premiership	Championship
01	W	W
02	L	W
03	W	W
04	L	W
05	W	W
06	L	W
07	L	W
08	L	W
09	W	W
10	W	W

A potential variable that has been suggested by previous research to influence player experience of HAEs, is whether the team won or lost the game (Abrahams et al., 2014; Hannah et al., 2019). This sample of games is distorted to 75% wins due to an unbeaten home season in the Championship. Regarding PLA, there was no statistically significant difference between match wins or losses (*p = 0.457, CI 95%*). In contrast, the difference in PAA observed between match wins and losses was considered statistically significant (*p = 0.022, CI 95%*).

5.3.2. Inter-Season Contact Event Linear Head Acceleration

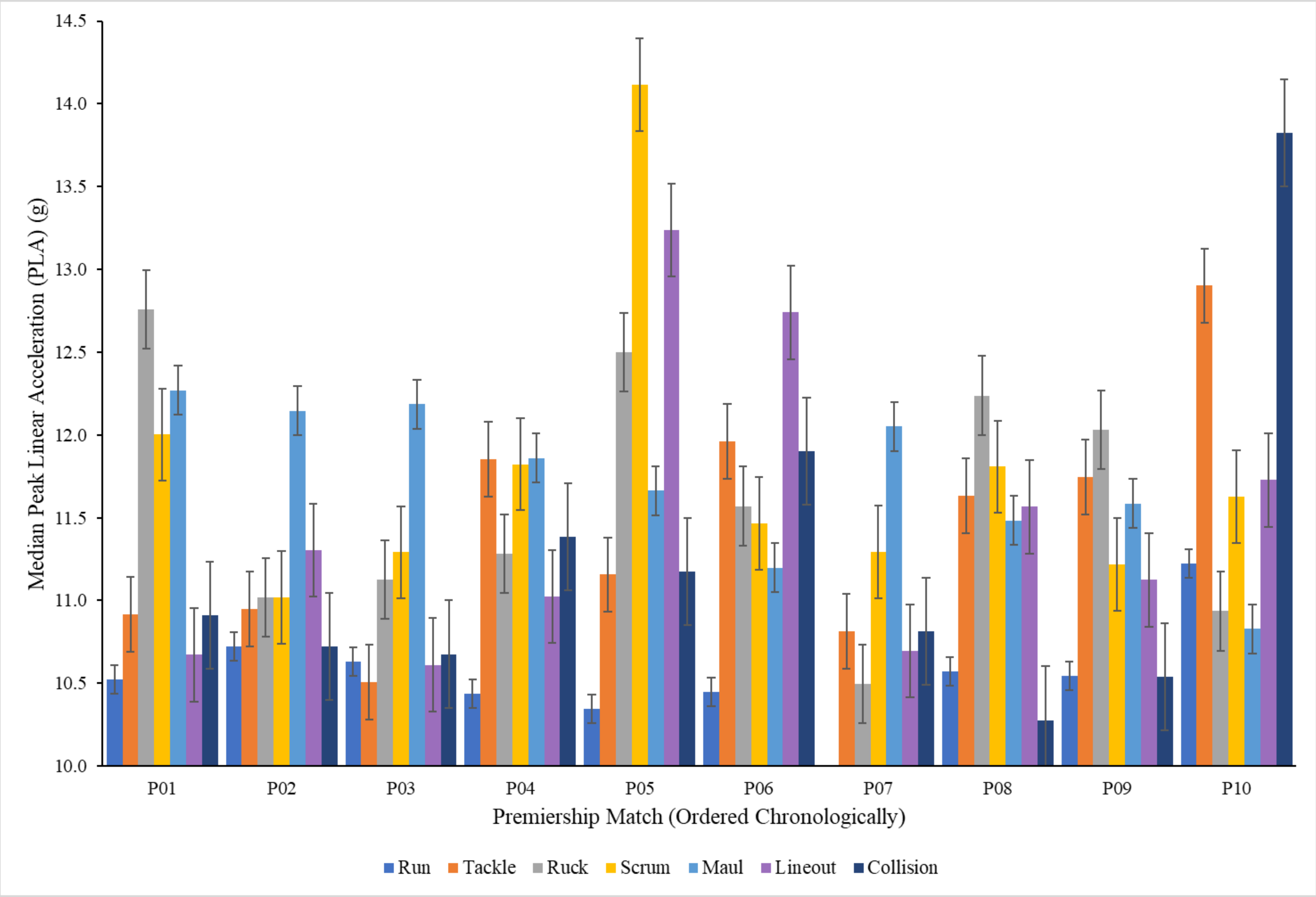

Figure 5.1. *Median PLA during different contact and non-contact events that resulted in an ITU trigger during Premiership matches.*

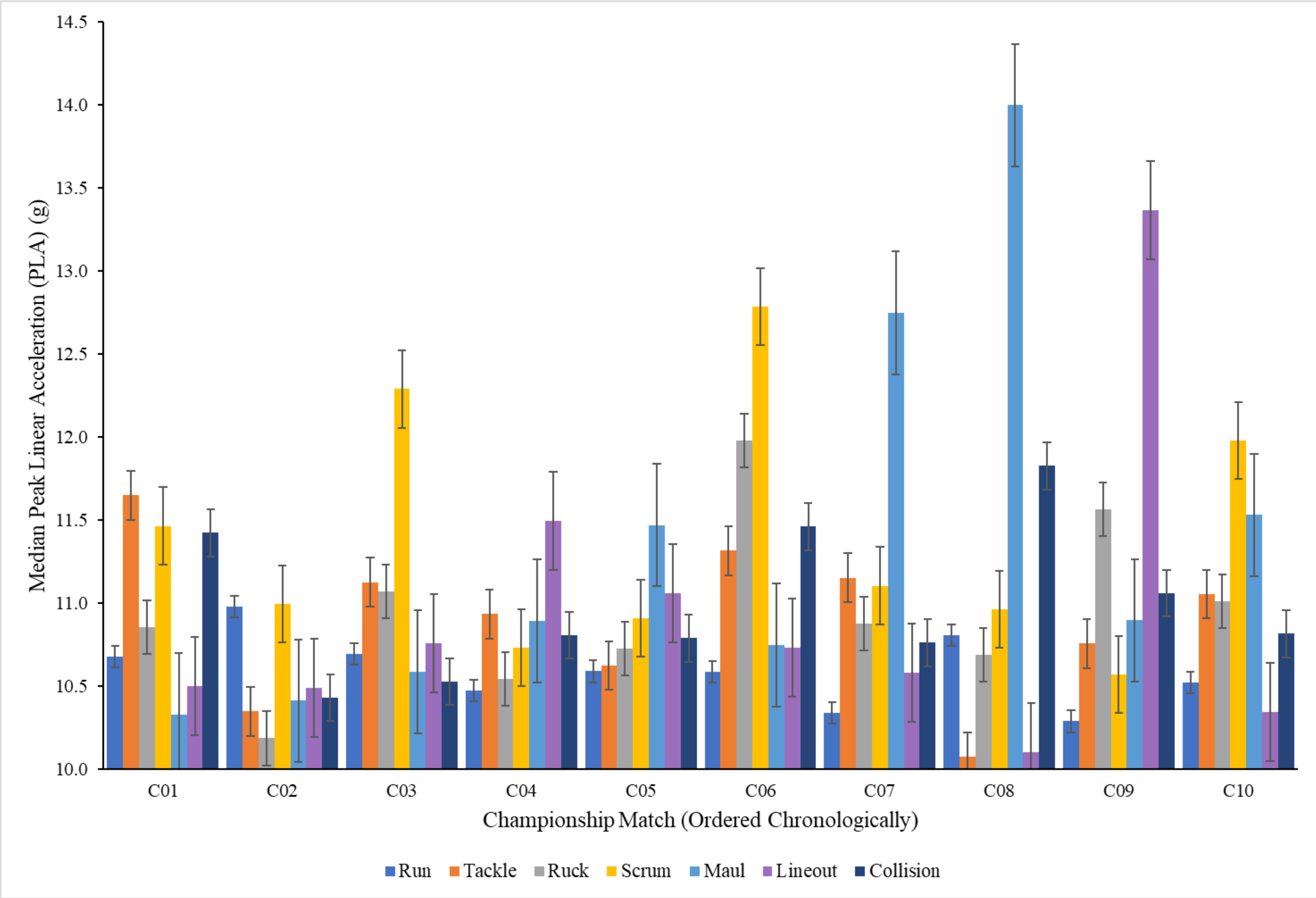

Figure 5.2. *Median PLA during different contact and non-contact events that resulted in an ITU trigger during Championship matches.*

Figure 5.1. and Figure 5.2. outline the variation in median PLA experienced during Premiership and Championship matches separated into the contact events discussed in Chapter 4. Overall, median PLA was higher in Premiership matches than in Championship matches. This difference in PLA magnitude was considered statistically significant (*p = 0.013*). In both tiers, cross-seasonal change in head acceleration magnitude is relatively minimal indicated by the similar match median PLA magnitudes between matches played at the beginning and end of seasons. There were several matches where median PLA across all contact events was raised, most notably, P05, P10 and P06. C06 would be considered elevated for the Championship season but only had a higher median PLA that three of the Premiership games. There were notable peaks in median PLA in different games associated with different contact events, for example, scrums during C03, P05, C06 and C10, collisions during P10, rucks during P01, and mauls during C07 and C08.

5.3.2.1. Tackle Events

Tackles were the most frequent contact event during each match. However, they did not have the greatest median PLA in any match with the exception of C01. Tackle PLA median magnitude was trending upwards throughout the Premiership season (range = 2.39g). Greatest tackle median PLA were seen in P04, P06 and P10. The difference in PLA experienced during tackle events in Premiership was considered statistically significantly more than in the Championship (*p = 0.018, CI 95%*). Median tackle PLA during the Premiership was consistent for the first three games of the season (range = 0.37g), with greater variation observed during the second three games (range = 0.78g). The final games of the season, excluding P10, have a slightly increased tackle PLA variation to the second three games of the season (range = 1.09g). P10 has the highest median PLA of all matches concerning the tackle area, but as indicated in Table 5.3., P10 also has the second highest contact event median PLA (11.97g, IQR: 1.23), only behind P05 (12.31g, IQR: 1.71). The difference in PLA between P10 and P05 is characterised by the high tackle and collision median PLA during P10, in contrast to the scrum, lineout and ruck PLA in P05. Median tackle PLA was notably lower during the Championship season, in addition to a decreased tackle PLA range across all Championship matches (range = 1.44g). The greatest tackle PLA was observed during C01 (11.65g, IQR: 0.57) with the lowest tackle PLA observed during C08 (10.11g, IQR: 0.33). There was no consistent uptrend or downtrend in tackle PLA across the Championship season. Slight, but non-significant peaks were seen in C01 (11.65g, IQR: 1.29) and C06 (11.32g, IQR: 2.09), but overall, median tackle PLA was consistent across all matches of the Championship season.

A Mann Whitney-U test indicated that there was no statistically significant difference in tackle PLA between Premiership and Championship (p = 0.64, *95% CI*). In addition, a Spearman's ρ was conducted to indicate the strength of the association between tackle PLA experienced in matches during the Premiership and Championship seasons when organised chronologically (P01 - C01, P02 - C02, et cetera.). The Spearman's ρ indicated no association between chronologically ordered median tackle PLA in Premiership and Championship matches and this lack of association was not considered statistically significant (r_s = -0.037, p = 0.92, n = 10). These findings indicate an overall similarity in the PLA experienced during tackle events in the Premiership and the Championship, however, the lack of association when ordered chronologically indicated an absence of consistency for when in the season the higher or lower tackle HAEs were occurring.

5.3.2.2. Ruck Events

The matches with the greatest median PLA associated with ruck events were P01, P05, P08, P09 and C06. Overall, ruck events had a higher median PLA during the Premiership (11.61g, IQR: 2.61) than in the Championship (11.01g, IQR: 1.8). Premiership ruck PLA varied between 10.49g (P07) and 12.76g (P01) whereas, Championship ruck PLA varied between 10.19g (C02) and 11.98g (C06) indicating a slightly increased variation in PLA during Premiership ruck events. A Mann-Whitney U test indicated a statistically significant difference in ruck PLA during the two seasons ($p = 0.043$, *95% CI*) suggesting higher PLA exposure in rucks in the Premiership. Similarly to the tackle events, the ruck events were organised chronologically by match and assessed to indicate if there was any association between the time in the season when a ruck event occurred and the PLA. The Spearman's ρ indicated no association between the position in the season when the match occurred and the magnitude of PLA when compared between the two seasons ($r_s = 0.12$, $p = 0.222$, $n = 10$). This result was not considered statistically significant.

5.3.2.3 Scrum Events

During the Premiership season, scrums had one notable peak in PLA during P05 that was significantly higher in terms of head acceleration experienced during scrums to the other matches in the Premiership ($p < 0.001$, *95% CI*). The greatest median PLA during scrums was observed during a Championship game, C06. However, the difference in magnitude of head acceleration during scrums in these two games remained statistically significantly higher in P05 ($p = 0.011$, *95% CI*). Median PLA during scrums remained relatively consistent across the Premiership season, excluding P05, ranging between 11.15g (IQR: 0.43) in P02, and 12.03g (IQR: 0.33) in P01. Similar consistencies in scrum PLA were observed during Championship games with a PLA range of 2.07g across all matches in the Championship. The scrum PLA range during the Premiership was 3.53g. Mann Whitney-U tests were conducted to indicate similarities between the PLA of Premiership scrums versus that of Championship scrums. The tests indicated no statistically significant differences between the PLA of scrums during the Premiership and the PLA of scrums during the Championship.

When comparing the games chronologically, there was also no significant associations found in PLA of scrums played at any point throughout the two seasons.

5.3.2.4. Maul Events

Mauls appeared to have a higher median PLA during Premiership matches, with the notable exceptions of C07 and C08, however, this difference was not considered significant (*p = 0.189, CI 95%*). Mauls were the contact events with the most similar median season PLA when comparing Premiership (11.77g, IQR: 3.11) and Championship (11.41g, IQR: 2.22) of all the contact events, excluding collisions. The greatest median PLA during mauls were observed in C08 (14.08g, IQR: 4.37) with the lowest median PLA during mauls were observed during C01 (10.65g, IQR: 3.99). The greatest Premiership median PLA during maul events was observed during P01 (12.27g, IQR: 1.84). Median PLA during mauls was relatively consistent across all Premiership matches (range = 1.44g) which was substantially lower than the variation observed across the Championship season (range = 3.68g). To understand the statistical relevance of these findings, further Mann Whitney-U tests were conducted to ascertain whether there was a true statistical relationship between the PLA experienced during maul events across the two seasons. The tests indicated no statistically significant differences between the PLA of mauls in the Premiership and the PLA of mauls in the Championship (*p = 0.082, 95% CI*). Similarly to other previously mentioned contact events, the maul events were compared chronologically by match order to determine if any association between median PLA experienced at a certain point in a season was reflected in both seasons. Ultimately, no relationship was observed between maul PLA and season match number.

5.3.2.5. Lineout Events

Lineouts are difficult to generalise in both seasons because the median PLA during each match varies so substantially. Other than a few standout results, PLA magnitude during lineouts regularly sat towards the lower end of the linear acceleration spectrum of contact events. The greatest median PLA during lineouts was observed during C09 with the lowest lineout related PLA identified a week earlier during C08. Premiership lineouts appeared to peak in median PLA during the middle part of the season (P05 and P06) before median PLA reduced to similar levels of the early season. Notwithstanding the peak result for lineout PLA during C09, Championship lineout PLA had a range of 0.96g, which would make lineouts one of the more consistent cross-season contact events concerning linear acceleration. A series of Mann Whitney-U tests were conducted to assess statistical differences between the PLA of lineouts during the Premiership and Championship seasons. No statistically significant differences regarding PLA were observed between Premiership and Championship matches.

5.3.2.6. Collision Events

Collision events were the most difficult to discern any real pattern but are necessary to investigate due to their abundance in this study (Chapter 5) and the evidence for their propensity for causing injury (Fuller et al., 2007). Median collision event PLA ranged between 13.81g (IQR: 0.89g) in P10 and 10.29g (IQR: 0.45g) in P08. Intra-seasonal ranges indicated that the Premiership variation (range = 3.54g) was higher than Championship (range = 1.4g). Median collision event PLA in the Championship was highest during C01 (11.42g). There were no statistically significant differences between collisions in the Premiership and collisions in the Championship regarding PLA ($p = 0.303$, *95% CI*).

5.3.3. Inter-Season Contact Event Angular Head Acceleration

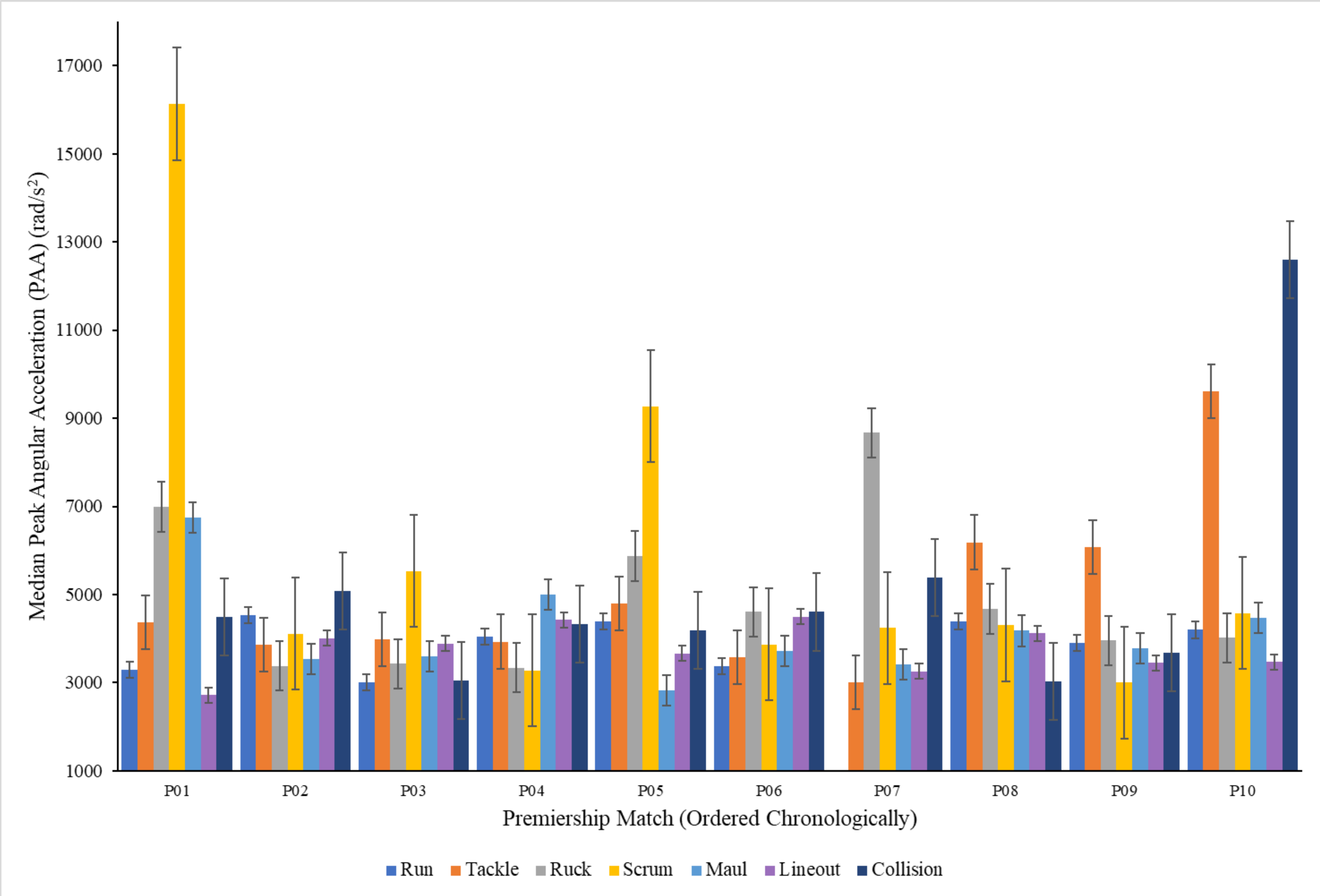

Figure 5.3. *Median PAA during different contact and non-contact events that resulted in an ITU trigger during Premiership matches.*

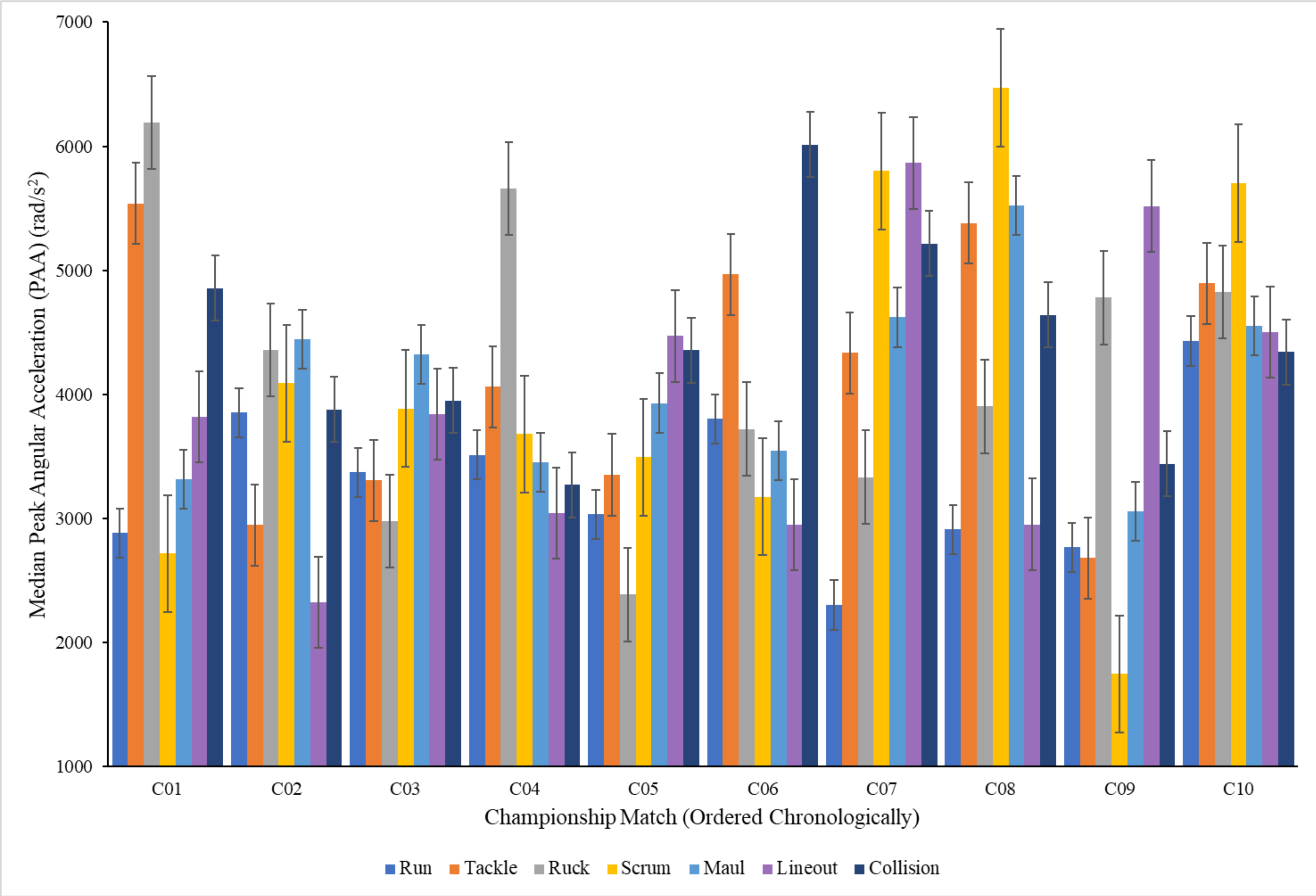

Figure 5.4. *Median PAA during different contact and non-contact events that resulted in an ITU trigger during Championship matches.*

Figure 5.3. and Figure 5.4. outline the variation in median PAA experienced during Premiership and Championship matches separated into the contact events discussed in Chapter 4. The most obvious and notable distinction between the two seasons is the indication of the high median PAA of scrum events during P01 and collision events during P10. Scrum events in P05, ruck events in P07, and tackle events in P10 all exceeded the maximum median PAA recorded during contact events that occurred in the Championship season. At 4600 rad/s^2 of angular acceleration, it has been suggested that there is a 25% probability of mTBI potential, increasing to a 50% probability if the PAA is increased to 5900 rad/s^2, and increasing again to an 80% probability if the PAA is increased to 7900 rad/s^2 (Zhang et al., 2004). If the extreme values were removed from the Premiership season, few contact events have median PAA values that exceeded 5900 rad/s^2 in either season. No events in the Championship season surpassed a median value of 5900 rad/s^2, the only contact event to have a median close to this boundary were scrum events during C08. It is necessary to emphasize here that these were median PAA values, multiple HAEs during contact events regularly exceeded these thresholds.

5.3.3.1. Tackle Events

Overall, tackle event median PAA ranged between 2684.84 rad/s^2 (IQR: 1998.76) (C09) and 9602.87 rad/s^2 (IQR: 2390.84) (P10). No Championship matches had tackle events with a median PAA exceeding the 5900 rad/s^2 threshold for a 50% probability of a player experiencing a mTBI. In contrast, the median PAA of three Premiership matches (P08, P09 and P10) exceeded this threshold during tackle events, with P10 exceeding the 7900 rad/s^2 threshold that is suggested to result in an 80% probability of mTBI. During the Premiership season, median PAA during tackle events was 4183.35 rad/s^2 (IQR: 1870.51 rad/s^2), whereas in the Championship season median PAA during tackle events was slightly higher at 4198.54 rad/s^2 (IQR: 1630.66 rad/s^2).

The range of PAA experienced during tackle events during the Premiership season was 6590.68 rad/s^2 with peaks in median PAA observed in the Premiership already mentioned during P08, P09 and P10. The minimum median PAA during tackle events that occurred during the Premiership season occurred during P07 (3102.19 rad/s^2, IQR: 1109.73). PAA during tackles remained relatively consistent for majority of the season, if the final three matches were to be excluded a range of 1781.54 rad/s^2 would have occurred. However, the uptrend in PAA magnitude observed towards the end of the season has potentially distorted the data to a point where it could appear to be significantly different from the Championship season. The range of PAA experienced during tackle events in the Championship season was 2854.38 rad/s^2 with no notable outlier results excluding the minimum Championship tackle PAA median of 2684.84 rad/s^2 (IQR: 1998.76) (C09). To identify if there was a significant difference between PAA magnitude during tackle events occurring in the Premiership or Championship, a Mann Whitney-U test was conducted. The test indicated that there was no statistically significant difference between PAA experienced during tackles in the Premiership and tackles in the Championship (*$p = 0.45$, 95% CI*).

5.3.3.2. Ruck Events

Ruck events median PAA ranged between 8671.42 rad/s (IQR: 3443.89) (P07) and 2387.99 rad/s^2 (IQR: 1432.75) (C05). In the Premiership season, ruck event median PAA were observed to be greater than 7900 rad/s^2 once (P07), greater than 5900 rad/s^2 but less than 7900 rad/s^2 not at all, greater than 4600 rad/s^2 but less than 5900 rad/s^2 in three matches (P01, P05, P06 and P08). The remaining games had median PAA during rucks less than 4600 rad/s^2 (P02, P03, P04, P09 and P10). The lower PAA matches appeared to be during the beginning of the season, excluding P01, before increases in ruck PAA were observed during the middle of the season and then decreases observed in the final two matches. In the Championship season, the median ruck event PAA ranged between the aforementioned C05 as the minimum ruck PAA in the sample, and C01 with a median PAA of 6190.99 rad/s^2 (IQR: 3274.85). The PAA experienced during ruck events was far more varied during the Championship season with no consistent up or downtrend throughout the season. For example, C02 had a median ruck PAA of 4359.64 rad/s^2 (IQR: 8467.55) which then decreased the following week (C03) to a median PAA of 2980.40 rad/s^2 (IQR: 2158.39) and then rebounded to a median PAA of 5658.78 rad/s^2 (IQR: 6308.25) in C04. The high levels of variability in the median PAA, notwithstanding the extreme variation indicated by the large IQR values, make it almost impossible to observe any consistent intra-season chronological trend. To indicate if there were any statistically significant differences between the PAA of rucks during the Premiership and Championship seasons, a series of Mann Whitney-U tests were conducted. The tests indicated that the Premiership rucks exposed the players to greater PAA than the rucks in the Championship season. This difference was considered statistically significant (*p = 0.006, 95% CI*).

5.3.3.3. Scrum Events

Describing PAA regarding scrum events is dominated by the incredibly high median PAA for scrums during P01 (16127.83 rad/s^2, IQR: 17621.17). The minimum median PAA for scrums was observed during C09 at 1749.96 rad/s^2, IQR: 11498.52). It would be remiss to avoid mentioning the large IQR values suggesting that even though P01 and C09 represent the extremes of median values, there was still significant variation within these matches.

During the Premiership season, median PAA range was 3916.11 rad/s^2 with the minimum PAA median during scrum events observed in P09 at 3006.12 rad/s^2 (IQR: 4098.68). There were three matches in the Premiership season which appeared as extremes in the data; the already mentioned P01, in addition to, P03 (5533.82 rad/s^2, IQR: 7634.97) and P05 (9267.57 rad/s^2, IQR: 13885.54). As with previous extreme angular acceleration values, the median

PAA values are accompanied with large IQR values which indicated large in-match variation in exposure to PAA during scrum events. Other than the extreme results, the remainder of the matches had median scrum event PAA separated by 1303.67 rad/s^2 with no obvious up or downtrend throughout the season. The Championship season scrum median PAA range was 4721.40 rad/s^2 with maximum scrum median PAA occurring during C08 (6471.36 rad/s^2, IQR: 6366.46) and minimum occurring during the previously mentioned C09. Scrum PAA was consistent during the first six matches of the Championship season with all matches' median PAA values situated between 2700 rad/s^2 and 4100 rad/s^2, or below the 25% probability of resulting in a mTBI. A Mann Whitney-U test was conducted to determine if there were statistically significant differences between the PAA of scrums during the two seasons. There was no statistically significant difference between the experience of PAA during the Premiership and Championship seasons (*p = 0.245, 95% CI*).

5.3.3.4. Maul Events

Premiership median maul PAA was 3750.53 rad/s^2 (IQR: 846.55), with a range of 3916.12 rad/s^2. Championship median maul PAA was 3783.97 rad/s^2 (IQR: 2043.18) with a range of 4721.40 rad/s^2. The seasonal differences in maul PAA tend to suggest that experience of angular acceleration was similar in terms of central tendency between the two seasons but varied far more during the Championship season. The maximum maul PAA median observed in the Premiership season was 6747.00 rad/s^2 (IQR: 11376.94) during P01. The minimum maul PAA median observed was 2830.88 rad/s^2 (IQR: 3884.21) during P05. With the exception of P01, median PAA during maul events ranged by 2169.12 rad/s^2 for the remaining nine matches. In the Championship, median PAA ranged between 5518.68 rad/s^2 (IQR: 5469.14) during C07 and 3058.77 rad/s^2 (IQR: 3589.46) during C09. Mann Whitney-U tests were conducted to assess the statistical significance of the differences observed across the two seasons. No statistically significant differences were observed concerning maul events during the Premiership and Championship seasons.

5.3.3.5. Lineout Events

Lineout median PAA during the Premiership was 3779.43 rad/s^2 (IQR: 633.96), whereas a median PAA of 3830.26 rad/s^2 (IQR: 1519.33) was observed during the Championship season. The range between match median PAA for lineout events in the Premiership was 1768.17 rad/s^2 in contrast to the range of 3538.21 rad/s^2 observed in the Championship. The maximum lineout median PAA occurred during C07 (5865.11 rad/s^2, IQR: 5639.63) with the minimum lineout median also occurring during the Championship in C02 (2326.91 rad/s^2, IQR: 3197.89). Maximum lineout median PAA in the Premiership occurred during P06 (4492.47 rad/s^2, IQR: 2456.42). Minimum Premiership median lineout PAA occurred during P01 (2724.29 rad/s^2, IQR: 2761.09). No statistically significant differences were observed between PAA of lineouts during the two seasons ($p = 0.398$).

5.3.3.6. Collision Events

Premiership median collision PAA was 4410.45 rad/s^2 (IQR: 1161.36), in contrast to 4348.27 rad/s^2 (IQR: 907.17) in the Championship season. The maximum observed median PAA for collision events in the Premiership was during P10 (12596.77 rad/s^2, IQR: 14380.81) indicating a substantial level of variability in collision angular acceleration. The maximum median PAA for collision events during the Championship occurred during C06 (6013.771 rad/s^2, IQR: 5655.14). During all matches, excluding P08 and P09, collision PAA was one of the two largest contributors to total match angular acceleration exposure out of all contact events. This was particularly evident in P02, P04 and P06 which without collisions contributing between 4000 - 5000 rad/s^2 per collision, would have had a substantially lower match median PAA. Collisions in Championship matches appeared to have relatively high

PAA in almost every match with the exception of C04 where the collision PAA was approximately 2400 rad/s^2 lower than the ruck PAA of the same match. Mann Whitney-U tests were completed to assess the statistical similarity between the PAA of collisions during the two seasons. No statistically significant differences were observed between collisions in the Premiership and collisions in the Championship (*p = 0.55, 95% CI*).

5.4. Summary

Overall, both PLA and PAA were higher during the Premiership season than in the Championship season. In contrast, total contact event frequency was higher during the Championship season than in the Premiership. Although the general trend of higher total contact frequency in the Championship is true, the most common contact events, as outlined in Chapter 4 and Table 5.1., the tackle and the ruck were both observed to have higher frequency in the Premiership. The contact events that dramatically increased the frequency during the Championship was the proportion of contact events identified as collisions and scrums. Paul et al. (2022) conducted a systematic review of papers where frequency of contact event was recorded for rugby union and rugby sevens. The data presented by Paul et al. (2022) suggested that contact events resulted in head telemetry trigger events in 22 scrums, 116 rucks and 156 tackles per match. This data suggests a contact event frequency substantially higher than during the Premiership or Championship season. The rugby sevens frequency data outlined by Paul et al. (2022) aligns more closely with the results of the Premiership and Championship seasons which evidently highlights some data presentation differences. This somewhat confusing theme is consistent with several leading papers in this field (Arbogast et al., 2022; King et al., 2017; Theadom et al., 2020; Tooby et al., 2022a; West et al., 2021). King et al. (2017) present the idea that at a semi-professional level, a player has a higher frequency of HAEs that what is observed at the amateur level even when the same players have competed for the same team which would differ from the data observed in this study. In addition, the trends highlighted in the highly cited paper by West et al. (2021) make reference to the increasing rate of HAEs observed in players that have played multiple seasons of professional rugby union potentially becoming a confounding factor. This argument is further compounded by the lack of acknowledgement that to become a professional rugby union player, multiple seasons of rugby would have been played prior to the season in which the player had any quantifiable measure of frequency of exposure to HAEs. This is a variable not considered in majority of the above-mentioned published studies and additional a limitation of this study. As no direct comparative, using an identical sample group within consecutive seasons, has been conducted between the two tiers of the English Premiership, there is no frequency data that can be directly compared to the results of this study. However, if it could be agreed that the Premiership and Championship of the English rugby pyramid are similar to other professional tiers, then some comparatives could be made in future research conducted with cohorts from developed rugby union nations where two professional leagues exist.

Overall, PLA during tackles was higher in the Premiership and notwithstanding the outlier median PAA during tackle events observed during P08, P09 and P10, angular head acceleration tended to be higher during the Championship season. During Chapter 4, it was highlighted that this participant group were involved in more tackles as tacklers rather than ballcarriers, however, the proportion of ballcarrier tackles is substantially higher in the Championship season. It was initially suggested in Chapter 3 that contact events where the player is unable to control the direction or orientation of the contact, thus being relatively unprepared for the impact, result in a higher magnitude of angular head acceleration. A potential explanation for the increase PAA during the Championship could be the difference in frequency of tackler roles observed between the two seasons. Across both seasons, tackle PLA was often a major contributor to total linear acceleration load (Chapter 6) and had the highest frequency of all contact events. However, tackle events never had the highest PLA except for C01 and are only had the highest median PAA during two Premiership matches. If these results are to be considered representative of two seasons of professional rugby, it appears somewhat of an oddity that majority of published literature (Moore et al., 2023; Quarrie and Hopkins, 2008; Ravin et al., 2022; Shah et al., 2020; Tierney et al., 2018; Tierney and Simms, 2017; Tierney and Simms, 2018; Tucker et al., 2017) focusses on the tackle when there are other contact events that could be considered as having a higher magnitude.

Ruck contact event variation between the two seasons indicated a higher mean frequency of rucks, a higher seasonal median PLA, and a higher seasonal median PAA during the Premiership season. Rucks events had the highest median PLA during three of the Premiership matches but did not have the highest PLA during any of the Championship matches. Conversely, from an angular acceleration perspective, ruck events had the highest median PAA during two Premiership matches and during three Championship matches. Seasonal variation in PLA was also larger in the Premiership. In line with the conclusions of Tooby et al. (2023), the relevance of rucks in the head acceleration telemetry picture is still unclear, but it requires further research particularly at a multi-tier level.

Of the remaining contact events, seasonal median PLA for scrums, mauls, lineouts and collisions was higher during the Premiership season. In somewhat of a contrast, seasonal median scrum PAA and collision PAA was higher during the Premiership but seasonal median PAA for mauls and lineouts was higher during the Championship season. There is often some similarity drawn between head acceleration experienced during mauls and lineouts due to their usual proximity. However, in P01, seasonally high maul PAA but then seasonally low lineout PAA was observed, even though 90% of mauls were formed when the lineout ends. The remainder of the matches in the Premiership saw, in some cases (P07), almost identical median PAA between lineouts and mauls. Overall, the greatest variation, represented by IQR, in PLA was observed during scrums (3.53g) in the Premiership season and during mauls (3.68g) in the Championship season.

All statistical tests indicate a lack of association between P01 vs C01, P02 vs C02 and so on. This is probably to be expected considering the number of confounding variables; the playing conditions, the opponent, the players participating in the HAE monitoring (Chapter 7), tactics employed, the list is to an extent, infinite. This could then eliminate the possibility that games played at the beginning, middle, and end of seasons, irrespective of the tier, result in similar experiences of PLA and PAA and the suggestion that the chronology or time point in the season has limited effect on experience of head acceleration. Further research to determine if there is any association between time in season and head acceleration experience would be required to understand this phenomenon.

Wins and losses did not appear to have any significant impact on the players experience of contact event frequency or PLA/PAA magnitude. However, there could be an argument proposed for wins resulting in lower exposure to head acceleration due to the lower magnitude or linear and angular head acceleration experienced during the unbeaten Championship season. Potentially a more appropriate metric would be to use score difference, where there may be more of trend of increase in head acceleration magnitude observed between matches that have a small score difference and those with a larger score difference. This analysis has not been included in this study, in part, to protect the anonymity of the players.

In the further analysis of the two seasons, where observations of which contact events differ inter-seasonally, there is very minimal difference that could be considered statistically significant. The large majority of differences that occurred implied exposure to PLA and PAA was similar in both seasons with the notable exceptions of PLA during tackles and PAA during rucks. Tackles and rucks are the most common type of contact event in this study, therefore if the sample was increased during the other contact events, this could potentially result in the other contact event types producing similar significant results. Although the traditional statistical processes suggest large sample size equals a more reliable data set, the drive towards *Big Data,* particularly in the field of head acceleration monitoring has the potential to result in high levels of inferential errors (Kaplan et al., 2014). These inferential errors often exist due to a systematic exclusion of information in order to compare a small number of variables whilst maintaining a large sample size. With all match-play head acceleration monitoring, the number of cofounding variables than must be considered before implying that one contact event results in a higher exposure to a certain type of acceleration is substantial.

To fully understand if any inter-season differences in acceleration magnitude exist, it may be prudent to examine it on an individual, per-player basis. The lack of significant differences between the contact events between seasons can largely be explained by the idea that because the same cohort of players are performing the contact events in each season, it is unlikely that there were any major differences from a macro perspective. However, investigation into individual players may highlight some more evident differences in contact event frequency and magnitude.

5.5. Link to the next chapter

In this chapter, the variable difference in frequency and magnitude of head acceleration events experienced by the same group of players competing at tier one and tier two of English domestic rugby has been examined. Significant research has been conducted to suggest that generalisation of mTBI is flawed and to appropriately understand the variation in head acceleration across professional rugby, a more individual interpretation is required. Throughout this chapter, there has been substantial reference to confounding variables and the impact that they may have on the outcome or interpretation of statistical tests, most notably, the variation caused by different players wearing the ITUs. Without an increased understanding of the impact of individual playing styles and positional differences, it will remain unclear what effect individuality will have on the exposure to head acceleration during contact events. Chapter 6 looks to highlight the inter-position group and inter-player position variation in head acceleration during professional rugby matches.

Chapter 6

Analysis of head acceleration exposure experienced professional rugby union player groups and player positions.

'Specificity is the soul of narrative.'

- John Hodgman. Actor, Author and Humourist. b.1971.

Chapter 6 - List of Tables & Figures

Table 6.8. *Combined ranking of frequency rank, PLA rank and PAA rank represented by player position.*

6.1. Introduction

Investigation into player position and injury largely groups players into forwards and backs with little reference to the individual demands of each player position. At the time of writing, eleven studies have reported on the differences between forwards and backs in terms of mTBI, eight of which reference professional rugby union (Bitchell et al., 2020; Cruz-Ferreira et al., 2018; Fuller et al., 2020; Fuller et al., 2017; Fuller et al., 2018; Schwellnus et al., 2019; Starling et al., 2021; West et al., 2021). None of these studies make any reference to individual positions or groups of positions that could be associated by playing demands (Duthie et al., 2003; Quarrie et al., 2013). Quarrie et al. (2013) suggest that contact load varies by position and that via a cluster-analysis of activities and time in motion, players can be grouped into ten subgroups of forwards and backs. Contact load in in the study conducted by Quarrie et al. (2013), refers to contact frequency and GPS velocity, outlined via video analysis. No reference to head acceleration magnitude was made because it was not recorded.

Studies focussing on individual physical match demands of rugby union players usually use a combination of total running distance (km), peak velocity (m/s), high speed running (HSR), metres per min (m/min^{-1}) and accelerations per min ($\frac{distance\ (d)}{time\ (t)}$/min) to categorise the different playing demands of each player (Pollard et al., 2018; Read et al., 2017b; Reardon et al., 2015). However, majority of studies in this area often draw significant conclusions between forwards and backs, not between individual positions.

From an anthropomorphic and physical characteristics standpoint, there are suggestions that forwards have a lower fat-free mass than backs and that forwards are significantly heavier and taller than backs (Zemski et al., 2015). Daniel et al. (2013) go further by suggesting that the props are the strongest position when assessed using bench press, box squat, back squat and chin-ups, but minor differences existed between the other positions. They go on to suggest a linear increase in speed as shirt number increases (prop = 1, fullback = 15) which aligned with a linear decrease in fat mass and fat percentage as shirt number increased. Neck strength has also been attributed to varying mTBI prevalence and recovery outcome with suggestions that poor isometric neck strength could be a risk factor for mTBI (Farley et al., 2022). Neck strength has been found to be greatest in forward players and has been used regularly to mitigate for cervical spine injuries (Naish et al., 2013). Chavarro-Nieto et al. (2021) and Garrett et al. (2023) both conducted systematic reviews to highlight the association between neck strength and mTBI. Chavarro-Nieto et al. (2021) concluded that although there is significant targeting of neck strength as a factor to decrease chance of mTBI, there is limited evidence to suggest a direct association between neck strength and mTBI. In support of this, Garrett et al. (2023) found a low certainty, nonsignificant relationship between increased neck strength and decreasing chance mTBI. Although no association has yet been proven between neck strength and mTBI, the differences in neck strength highlight further the differences in physical characteristics between positions.

Although there is minimal agreement across published literature regarding player position and prevalence of mTBI, there is consensus on physical and anthropomorphic characteristics and match role demands. Differences in mTBI frequency and contact event frequency have been highlighted between forwards and backs, but further research is necessary to understand differences between individual positions. The characterizable differences between positions propose the idea that head acceleration frequency and magnitude could vary between positions. The aim of this chapter is to highlight the differences in PLA, PAA and frequency of contact events between the player groups and player positions during the two seasons of professional rugby union. Once this has be examined, a hypothetical scenario will be outlined to highlight the potential cumulative head acceleration load experienced over a career of professional rugby union.

6.2. Player Group Comparison

The first results from this chapter look to highlight the inter-group differences between the various player groups by examining the PLA, PAA, and contact event frequency experienced within each player group. As a reminder of the player groups and the positions contained within each player group from Chapter 2; front row forwards (props and hookers) are Group 1 (G1), second row forwards (locks) are Group 2 (G2), back row forwards (flankers and number eights) are Group 3 (G3), half-backs (scrum-half and fly-half) are Group 4 (G4), centres (inside and outside) are Group 5 (G5), and back three players (wing and fullback) are Group 6 (G6).

Table 6.1. *Median PLA and PAA exposure during Championship and Premiership seasons organised by player group.*

Group	PLA (IQR) (g)	PLA Rank	PAA (IQR) (rad/s^2)	PAA Rank
2	10.95 (2.45)	1	4343.82 (4683.20)	2
3	10.93 (2.33)	2	4359.34 (4523.09)	1
1	10.91 (2.06)	3	4066.48 (3650.32)	4
5	10.75 (1.83)	4	4178.34 (4376.47)	3
4	10.71 (1.58)	6	3659.02 (3409.25)	5
6	10.73 (1.79)	5	3436.87 (3407.50)	6

†*Groups are ordered in Table 6.1. by combined PLA and PAA rank. G2 with the highest combined rank and G6 with the lowest.*

Basic descriptive statistics indicate player groups containing forwards to have higher PLA than player groups containing backs. In contrast, PAA is more varied across all player groups; G5 has a higher median PAA than G1, but then G2 and G3 have higher median PAA than the remaining player groups. To indicate if these differences could be considered statistically significant, a series of pairwise Mann Whitney-U tests were completed.

Table 6.2. *Inter player group median differences in PLA and PAA and significance values following Mann Whitney-U tests.*

Group Comparison	Difference in PLA	Significance		Group Comparison	Difference in PAA	Significance
G2-G4	0.243	$p < 0.001$		G3-G6	922.465	$p < 0.001$
G3-G4	0.226	$p < 0.001$		G2-G6	906.950	$p < 0.001$
G2-G6	0.213	$p < 0.001$		G5-G6	741.461	$p < 0.001$
G1-G4	0.203	$p < 0.001$		G3-G4	700.321	$p < 0.001$
G3-G6	0.197	$p < 0.001$		G2-G4	684.806	$p < 0.001$
G2-G5	0.194	$p < 0.001$		G1-G6	629.608	$p < 0.001$
G3-G5	0.178	$p < 0.001$		G5-G4	519.317	$p < 0.001$
G1-G6	0.173	$p \leq 0.001$		G1-G4	407.464	$p < 0.001$
G1-G5	0.154	$p = 0.003$		G3-G1	292.857	$p < 0.001$
G5-G4	0.049	$p = 0.107$		G2-G1	277.342	$p < 0.001$
G2-G1	0.040	$p = 0.009$		G4-G6	222.144	$p < 0.001$
G6-G4	0.029	$p = 0.063$		G3-G5	181.004	$p = 0.171$
G3-G1	0.024	$p = 0.104$		G2-G5	165.489	$p = 0.518$
G5-G6	0.019	$p = 0.915$		G5-G1	111.853	$p = 0.008$
G2-G3	0.016	$p = 0.222$		G3-G2	15.515	$p = 0.533$

[†]*$\alpha = 0.05$, CI = 95%*

[††]*Comparisons are ordered by descending order of difference in PLA or PAA magnitude. The first player group listed in the comparison has the higher median magnitude.*

Statistically significant differences in PLA and PAA were observed between G1 and all other player groups except G3. Additionally, significant differences in both PLA and PAA were observed between G2-G4, G2-G6, G3-G4 and G3-G6. Significant differences only in PLA were observed between G2-G5 and G3-G5, whereas significant differences only in PAA were observed between G3-G1, G5-G4, G6-G4, and G5-G6. There were no statistically significant differences in PLA and PAA observed between G2-G3. Also, there were no significant PLA differences between G4-G5 and G4-G6 but in both cases differences in PAA were observed as significant. Considering the differences between forwards (G1, G2 & G3) and backs (G4, G5 & G6), forwards had statistically significantly higher exposure to PLA in all pairwise comparisons. The differences between forwards and backs concerning PAA was statistically significantly higher between forward player groups and G4 and G6. In contrast, G5 PAA was significantly statistically significantly different from forward player groups, but median PAA was higher than G1 median PAA.

Table 6.3. *Relative event frequency of major contact events represented by player groups.*

Group	Tackle	Ruck	Scrum	Maul	Lineout	Collision
3	65	56	24	31	9	38
2	53	55	22	36	25	28
1	46	47	30	33	7	25
6	58	30	0	3	0	30
5	49	30	0	2	0	33
4	43	19	0	2	0	38

†*Relative frequency = n of CE per match/n of Group*

††*n = G1(15), G2 (10), G3(14), G4(12), G5(9), G6(14)*

†††*Groups are ordered in Table 7.3. by combined CE frequency. G3 with the highest combined frequency rank and G4 with the lowest.*

From a relative contact event-position group perspective, the players who involved in the most tackles and the most rucks that resulted in a ITU triggered event were from G3. G2 players involvement in maul and lineout events resulted in the most ITU triggers when compared to other player groups. Potentially as expected, G1 players had the highest scrum event frequency, however, G1 players also had a relatively low tackle frequency as it appeared similar to G4 and G5. G6 tackle frequency was relatively high compared to other player groups with only G3 players involved in more tackle events. The inter-group differences in tackle frequency could be highlighted by the player role within tackle events.

Somewhat against the trend of the findings presented so far in this chapter, G3 and G4 received the same relative frequency of collisions unrelated to the major contact events.

Table 6.4. *Relative tackle event frequency represented by player role and player group.*

Group	Ballcarrier Relative Frequency	Tackler Relative Frequency
1	21	25
2	21	32
3	28	37
4	13	30
5	22	27
6	31	27

G1, G2, G3, G4 and G5 all made more tackles than carried the ball into contact during tackle events. The only group that ball carried into tackles more often than making tacklers was G6.

Overall, observations indicated that G3 had the highest frequency of contact events, in addition to being exposed to the highest median PAA and the second highest median PLA. G3 contact events were significantly higher in PLA and PAA than all other groups with the exception of G2. G2 had the second highest frequency, the second highest median PAA and the highest median PLA. G4 players were involved in the lowest frequency of contact events and had low magnitude of PLA and PAA. G5 players had a median PLA exposure similar to the other backs player groups but had the third highest median PAA. G3 players were involved in the most tackles and the most rucks, whereas G2 players were involved in the most mauls and lineouts. G1 players were involved in the most scrum events with collisions not associated with other major contact events were relatively consistent across all player groups. All player groups were more likely to be the tackler in tackle events with the exception of G6 players who were more likely to be the ballcarrier.

6.3. Player Position Comparison

The following section separates the player groups by position to identify if any particular position within a high or low head acceleration ranked player group deviates from other related positions. Inter-group player positions linear and angular head acceleration were analysed and statistical significance, where it occurred, highlighted.

Table 6.5. *Median PLA and PAA magnitude and PLA and PAA magnitude rank during Championship and Premiership seasons.*

Position	PLA (IQR) (g)	PLA Rank	PAA (IQR) (rad/s^2)	PAA Rank
Lock	10.948 (2.45)	1	4343.822 (4683.20)	2
Tighthead	10.947 (2.05)	2	4210.179 (3810.24)	3
Number 8	10.930 (2.32)	4	4654.935 (4440.10)	1
Flanker	10.934 (2.34)	3	4184.919 (4568.12)	4
Fullback	10.845 (1.94)	6	4115.938 (3803.47)	6
Centre	10.754 (1.83)	8	4178.333 (4376.47)	5
Hooker	10.840 (2.13)	7	3895.811 (3590.03)	7
Loosehead	10.873 (1.94)	5	3349.786 (1748.52)	10
Scrum-Half	10.751 (1.58)	9	3440.137 (3286.91)	9
Fly-Half	10.698 (1.57)	11	3821.939 (3508.96)	8
Wing	10.702 (1.67)	10	3173.549 (3182.33)	11

†*Positions are ordered in Table 7.5. by combined PLA and PAA rank. Locks with the highest combined rank and wings with the lowest.*

Locks had the highest median PLA and second highest median PAA behind number eight players. The variability in PAA was larger for locks than any other player position but IQR in PLA was observed to be relatively low in comparison to other positions. Tighthead props ranked highly in both median PLA and PAA, however, loosehead props placed approximately in the middle of all positions regarding PLA and tenth overall in median PAA. Loosehead PAA also had a low level of variability indicated by the smallest IQR value. Number eights and flankers sit highly in combined PLA and PAA rank but with number eight players tying tightheads for second overall. Centres have a relatively low median PLA, with low variability, but have a contrastingly high median PAA ranking only behind the four major contact positions already mentioned. Hookers and looseheads place relatively low in terms of PLA and PAA compared to other forwards with similar game roles and body compositions, for example, tightheads. The median PAA for looseheads was more similar in magnitude to scrum-halves and wings that to their prop counterparts on the other side of the scrum. Ranked the lowest in combined PLA and PAA rank were the positions of G4 (scrum-half and fly-half) and wings. The only notable deviation from the low ranked positions is the PAA experienced by fly-halves, which was similar in magnitude and variability to hookers.

Table 6.6.i. *Position median differences in PLA (g) and PAA (rad/s^2) and significance values following Mann Whitney-U tests.*

Position Comparison	Difference in PLA	Significance		Position Comparison	Difference in PAA	Significance
L-FH	0.250	$p < 0.001$		N8-W	1481.39	$p < 0.001$
TH-FH	0.249	$p < 0.001$		N8-LH	1305.15	$p < 0.001$
TH-W	0.245	$p < 0.001$		N8-SH	1214.80	$p < 0.001$
F-FH	0.236	$p < 0.001$		L-W	1170.27	$p < 0.001$
N8-FH	0.232	$p < 0.001$		TH-W	1036.63	$p < 0.001$
F-W	0.232	$p < 0.001$		F-W	1011.37	$p < 0.001$
N8-W	0.228	$p < 0.001$		C-W	1004.78	$p < 0.001$
TH-SH	0.196	$p \leq 0.001$		L-LH	994.04	$p = 0.002$
L-C	0.194	$p < 0.001$		FB-W	942.39	$p < 0.001$
TH-C	0.193	$p = 0.002$		L-SH	903.69	$p < 0.001$
F-SH	0.183	$p < 0.001$		TH-LH	860.39	$p = 0.003$
F-C	0.180	$p < 0.001$		F-LH	835.13	$p = 0.006$
N8-SH	0.179	$p < 0.001$		N8-FH	833.00	$p < 0.001$
N8-C	0.176	$p < 0.001$		C-LH	828.55	$p = 0.005$
LH-FH	0.175	$p = 0.493$		TH-SH	770.04	$p < 0.001$
L-W	0.171	$p < 0.001$		FB-LH	766.15	$p = 0.016$
LH-W	0.171	$p = 0.746$		N8-H	759.12	$p < 0.001$
FB-FH	0.148	$p = 0.005$		F-SH	744.78	$p < 0.001$
FB-W	0.144	$p = 0.045$		C-SH	738.20	$p < 0.001$
H-FH	0.142	$p = 0.004$		H-W	722.26	$p < 0.001$
H-W	0.138	$p = 0.032$		FB-SH	675.80	$p < 0.001$
LH-SH	0.122	$p = 0.721$		FH-W	648.39	$p < 0.001$
L-SH	0.122	$p < 0.001$		H-LH	546.03	$p = 0.143$
LH-C	0.119	$p = 0.947$		N8-FB	539.00	$p < 0.001$
L-H	0.108	$p = 0.015$		L-FH	521.88	$p < 0.001$
TH-H	0.107	$p = 0.341$		N8-C	476.60	$p = 0.001$
TH-FB	0.102	$p = 0.277$		FH-LH	472.15	$p = 0.101$
FB-SH	0.094	$p = 0.058$		N8-F	470.02	$p < 0.001$
F-H	0.094	$p = 0.201$		H-SH	455.67	$p \leq 0.001$
FB-C	0.091	$p = 0.149$		L-H	448.01	$p < 0.001$
N8-H	0.090	$p = 0.056$		N8-TH	444.76	$p < 0.001$
H-SH	0.089	$p = 0.049$		TH-FH	388.24	$p \leq 0.001$
F-FB	0.088	$p = 0.142$		FH-SH	381.80	$p < 0.001$
H-C	0.086	$p = 0.122$		F-FH	362.98	$p < 0.001$

Table 6.6.ii. *Position median differences in PLA (g) and PAA (rad/s^2) and significance values following Mann Whitney-U tests* (Continued).

Position Comparison	Difference in PLA	Significance		Position Comparison	Difference in PLA	Significance
N8-FB	0.085	*p = 0.033*		C-FH	356.39	*p < 0.001*
L-LH	0.075	*p = 0.19*		TH-H	314.37	*p < 0.001*
TH-LH	0.074	*p = 0.394*		N8-L	311.11	*p = 0.005*
F-LH	0.061	*p = 0.363*		FB-FH	294.00	*p = 0.071*
N8-LH	0.057	*p = 0.227*		F-H	289.11	*p < 0.001*
C-FH	0.056	*p = 0.083*		C-H	282.52	*p < 0.001*
SH-FH	0.053	*p = 0.483*		SH-W	266.59	*p = 0.002*
C-W	0.052	*p = 0.476*		L-FB	227.88	*p = 0.01*
SH-W	0.049	*p = 0.806*		FB-H	220.13	*p = 0.028*
LH-H	0.033	*p = 0.653*		LH-W	176.24	*p = 0.137*
LH-FB	0.028	*p = 0.667*		L-C	165.49	*p = 0.518*
L-FB	0.028	*p = 0.009*		L-F	158.90	*p = 0.257*
L-N8	0.018	*p = 0.668*		L-TH	133.64	*p = 0.147*
TH-N8	0.017	*p = 0.211*		TH-FB	94.24	*p = 0.19*
L-F	0.014	*p = 0.136*		SH-LH	90.35	*p = 0.857*
TH-F	0.013	*p = 0.653*		H-FH	73.87	*p = 0.569*
FB-H	0.005	*p = 0.892*		F-FB	68.98	*p = 0.101*
W-FH	0.004	*p = 0.274*		C-FB	62.39	*p = 0.066*
F-N8	0.004	*p = 0.378*		TH-C	31.85	*p = 0.533*
C-SH	0.003	*p = 0.441*		TH-F	25.26	*p = 0.745*
L-TH	0.001	*p = 0.064*		F-C	6.59	*p = 0.676*

[†]*TH = Tighthead, H = Hooker, LH = Loosehead, L = Lock, F = Flanker, N8 = Number Eight, SH = Scrum-Half, FH = Fly-Half, C = Centre, W = Wing, FB = Fullback*

[††]*α = 0.05, CI = 95%*

[†††]*Comparisons are ordered by descending order of difference in PLA or PAA magnitude. The first position listed in the comparison has the higher median magnitude.*

The data outlined in Table 6.6.i and 6.6.ii indicates the PLA and PAA pairwise comparisons of the different positions and the associated significance. Of the fifty-five combinations, nineteen tests returned significant results for both PLA and PAA, twenty-one tests returned significant results only for difference in PAA, five tests returned significant results only for difference in PLA, and ten tests returned no significant results for difference in either PLA or PAA.

Difference in both PLA and PAA

Significant difference in both PLA and PAA was observed between number eights and all back positions. Flankers and tightheads observed significant difference in PLA and PAA with all back positions excluding centres and fullbacks. Locks observed significant difference in PLA and PAA with all back positions, excluding centres, and also with hookers. Hookers also observed significant difference in PLA and PAA with scrum-halves and wings. Somewhat unexpectedly due to the positions being in the same player group, wings and fullbacks also observed significantly differences in PLA and PAA.

Difference in only PLA

Tightheads, locks and flankers only observed significant differences in PLA with centres. Fly-halves also only observed difference in PLA with hookers and fullbacks.

Difference in only PAA

Difference in only PAA was the most common outcome from the series of Mann Whitney-U pairwise comparisons. Tightheads only observed PAA differences with looseheads, hookers and number eights. Hookers and looseheads observed just PAA differences with flankers, number eights, centres and fullbacks, with the only comparative difference between hookers and looseheads occurring with a significant PAA difference observed between looseheads and locks. Number eights also had significant differences in PAA observed with locks and flankers and scrum-halves observed differences in PAA with all other back positions. Fly-halves saw PAA differences in with centres and wings, and centres observed a PAA difference with wings.

No significant difference in PLA or PAA

No significant PLA or PAA differences were observed between tightheads and locks, flankers or fullbacks. Likewise, no significant difference was observed between looseheads and hookers, scrum-halves, fly-halves and wings. There were also no significant differences observed between locks and flankers, centres and fullbacks, and flankers and fullbacks.

Table 6.7. *Relative event frequency of major contact events represented by player positions.*

Group	Tackle	Ruck	Scrum	Maul	Lineout	Collision
Flanker	71	56	28	35	12	40
Tighthead	53	58	31	45	9	26
Lock	53	55	22	36	25	28
Number Eight	57	56	19	25	6	34
Fly-Half	78	32	0	2	0	62
Hooker	43	37	25	17	7	17
Loosehead	28	30	27	28	4	28
Fullback	62	41	0	3	0	27
Centre	55	33	0	2	0	37
Wing	56	23	0	2	0	32
Scrum-Half	20	10	0	2	0	21

†*Relative frequency = n of CE per match/n of Position*

††*n = TH(6), H(5), LH(4), L(10), F(8), N8(6), SH(8), FH(4), C(9), W(9), FB(5)*

†††*Positions are ordered in Table 6.7. by combined CE frequency. Flankers with the highest combined frequency rank and scrum-halves with the lowest.*

Flankers, fly-halves and fullbacks were involved in the most tackle events. Flankers main role was the tackler (16 ballcarrier, 55 tackler), fly-halves tackle role was mixed (37 ballcarrier, 41 tackler), and fullbacks main role was most commonly as a ballcarrier (40 ballcarrier, 22 tackler). The least involvement in tackle events was seen from scrum-halves and unexpectedly, from loosehead props. Ruck event involvement was dominated by the major four contact positions: lock, tighthead, flanker and number eight. Centres and fullback led the ruck involvement for the backs. Scrums and lineouts only saw forward involvement with tightheads observed to have the highest frequency of scrum events and locks having the highest frequency of lineout events. Random collisions were notably higher for fly-halves when compared to all other positions. Twenty-two more collisions events occurred to fly-halves than the second most collision-frequent position, flankers, which had a collision frequency similar to that of several other positions.

Table 6.8. *Combined ranking of frequency rank, PLA rank and PAA rank represented by player position.*

Position	Frequency Rank	PLA Rank	PAA Rank	Combined Rank
Lock	3	1	2	6
Tighthead	2	2	3	7
Flanker	1	3	4	8
Number Eight	4	4	1	9
Hooker	6	7	7	20
Fullback	8	6	6	20
Loosehead	7	5	10	22
Centre	9	8	5	22
Fly-Half	5	11	8	24
Scrum-Half	11	9	9	29
Wing	10	10	11	31

†*Positions are ordered in Table 6.8. by combined CE frequency, PLA rank and PAA rank. Locks with the highest combined rank and wings with the lowest. Tie breaks are resolved by the position with the higher CE frequency placed above the position with the lower CE frequency.*

The combined position rank is the sum of relative contact event frequency rank, per contact event PLA rank and per contact event PAA rank. Locks, tightheads, flankers, and number eights have combined ranks far lower than any of the other positions indicating that these positions have high PLA and PAA, and high frequency of contact event involvement. There is minimal variation in the combined rank of hookers, fullbacks, looseheads, centres, and to a lesser extent fly-halves. Fly-halves have a high frequency of contact event involvement but a low PLA and PAA magnitude. Scrum-halves and wings have the lowest combined rank regularly sitting at the lower end of magnitude and frequency rankings with scrum-halves observed to experience higher magnitudes of PLA and PAA, whereas wings are more frequently involved in contact events.

6.4. Discussion

This chapter outlines the differences in head acceleration experienced between various player positions and positional groups. As a general theme, in line with previously published research (Bitchell et al., 2020; Fuller et al., 2020; West et al., 2021), forwards were involved in more contact events and were exposed to higher PLA and PAA than backs. Between the six different positional groups, G2 players had the highest PLA and the second highest PAA during contact events, whereas, G3 players had the highest PAA and the second highest PLA of the positional groups. G1 players and G5 players were similar in combined group rank as G1 players ranked third in PLA and fifth in PAA, whereas the reverse was true for G5 players. However, G1 players ranked third in contact event frequency compared to G5 players ranking fifth. G4 and G6 players ranked fifth and sixth regarding PLA (G4 = 6th, G6 = 5th) and PAA (G4 = 5th, G6 = 6th), however, G6 players were involved in the fourth most contact events per player.

G2 and G3 players were very similar across all head accelerations and contact event metrics and whilst considering an ethnographic perspective, this was expected. When observing the matches, G2 and G3 players were noted to have similar roles. In lineout events for example, one lineout would see a G2 player lifted by a G3 player and then the following lineout would see the reverse. In the tackle area, G3 players were more likely to carry the ball into contact whereas G2 players were more likely to be the tackler. The similarities between these two groups were potentially magnified by the propensity for players to sometimes switch between G2 and G3 depending on selection and squad injuries. Although then expected to perform different roles in set plays, for example, during scrums and lineouts, the players' open field characteristics and contact event involvements did not change significantly.

The differences between G1, and G2 and G3 were more pronounced with significant differences in PLA observed between G1 and G2 but not between G1 and G3. G1 players also experienced significantly lower PAA during contact events than G2 and G3 players. Of all forward players, distinguishing the front row players in terms of match roles and physical characteristics from the remaining forwards is far easier than observing differences between G2 and G3 players. For example, G1 players mean weight was 120 kg and mean height was 183 cm. In contrast, G2 players mean weight was 116 kg and mean height was 198 cm, whereas G3 players mean weight was 110 kg and mean height was 190 cm. On average, G1 players are shorter and heavier than G2 and G3 players. G1 players also cover the least amount of total distance and play the least amounts of minutes per match (Cahill et al., 2013). This suggestion is consistent with published literature that indicates that forwards have higher body mass, fat-free mass and body fat percentage than backs (McHugh et al., 2021). Although none of these characteristics have been proven to have any influence over head acceleration events, if there are physiological differences between individuals and the roles that they perform around the pitch differ also, then a player's experience of head acceleration could also vary.

An area that potentially requires further examination is the significant difference in PAA between G1, and G2 and G3 players. At the time of writing, there does not appear to be any published explanation why G1 players experience of PAA would vary significantly from the other forwards. However, Cecchi et al. (2021) during a trial with collegiate American football players highlights that skill position players, for example, wide receivers or quarterbacks typically have higher PAA than linemen. G1 players are far similar in terms of body composition and match roles to linemen than they are to American Football skill position players. Therefore, following the trend of a lower PAA could potentially be expected. The roles that G1 players perform around the pitch are more strength reliant, for example, supporting in excess of 8000 N generated by opposing packs during scrums (Martin and Beckham, 2020). To generate the strength necessary to support the scrum, G1 players are generally heavier and less mobile around the pitch. Therefore, it would be unlikely for G1 players to be involved in more contact events that G2 and G3 players. G1 players greatest number of non-set piece contact events came from pod carries, covering between five metres between receiving the ball from another player and then making contact with an opposition player. This short but direct carrying style was indicative of all G1 players. From the video analysis, the body position during these short carries tended to be more dipped when G1 players carried into the tackle, whereas G1 players tended to be more upright when acting as the tackler. As was observed from Chapter 5, a higher contact height when making a tackle exposes both tackler and ballcarrier to higher head acceleration and so this upright tackling style may explain why G1 players experience high magnitudes of PAA.

Regarding linear acceleration for backs, all player groups containing backs were lower in PLA than player groups containing forwards. The greatest inter-group difference in PLA between back player groups was observed between G5 and G4 but this was not considered to be significant. No significant differences in PLA were recorded between any of the back player groups. In contrast, G6 players had a lower median PAA than all other player groups with the most notable significant differences observed with G3, G2 and G5. The differences in PAA between G6, and G1 and G4 were still significant but the magnitude of difference was lower. G5 players had a higher PAA than all other player groups excluding G3 and G2, although the differences between G5 an G2 were not considered significant. G4 had a high PAA than G6 but then statistically significantly lower PAA than all other player groups.

The lack of difference in PLA, but then notable significant differences observed in PAA between back player groups is difficult to explain. However, as outlined in Chapter 4, there does not appear to be any linear relationship between increasing PLA and increasing PAA within a contact event but only between contact events. The high PAA experienced by G5 is somewhat distorted by the high median PAA experienced by two G5 players: TG14 and TG73. Both TG14 and TG73 had median PAA magnitudes notably higher than the group average at 7504.66 rad/s^2 and 8008.13 rad/s^2 respectively. With G5 having the smallest number of participants, it could be argued that these two outlier players have more of an effect on the group's expected PAA than other players have in larger participant groups.

G4 and G6 could be considered low magnitude and low frequency concerning contact events, however, there is significant variation within groups between positions. Using the example of fly-halves and scrum-halves in G4, scrum-halves have a much lower contact event frequency than fly-halves, but no statistically significant differences were observed between PLA experienced by the two player positions. In contrast, fly-halves experienced significantly higher PAA than scrum-halves. Another observation that appeared to differ from previously published literature, was the numerous tackle involvement of fly-halves both as ballcarriers and tacklers. Noted throughout the video analysis stage of this research was the propensity for fly-halves to act as the "first receiver" from the base of set pieces and rucks, in addition to acting as a target channel for back row players carrying the ball from set pieces, for example, immediately after scrums. Fly-halves were involved in the third least contact events overall, highlighting that although these players were involved in a high frequency of tackle events, they were involved in a low frequency of other contact event types, namely, rucks and mauls. In contrast, scrum-halves were involved in fewer contact events, but their contact event involvement was more diverse, with significantly more involvement in the form of rucks and collisions that their G4 counterparts. For a player group that has been suggested to be low magnitude and low frequency, there were still occasions where G4 players experienced high PAA and PLA than would be comparable with forward player groups.

Wings and fullbacks occupy the same position group but differ significantly in terms of PLA (0.144 g, $p = 0.045$) and PAA (942.39 rad/s^2, $p < 0.001$) with fullbacks in both metrics. In contrast to G4, G6 positions did not vary significantly in terms of contact event frequency. Once again, when observing G6 players during the video analysis stage, no notable player characteristics or distinguished wings from fullbacks and vice versa. The differences observed in player characteristics were player specific, rather than position specific. For example, TG11, TG14, TG17 and TG20 all occupy G6 and were involved in both seasons of this study, playing in over half the games recorded. The experience of head acceleration varied significantly between all four players with TG11 and TG14 playing as wings and TG17 and TG20 playing as fullbacks. Both TG17 and TG20 were involved in more tackles and rucks than TG11 and TG14, however, both wings were more likely to carry into a tackle than to be the tackler, whereas the opposite was observed for the fullbacks. The variation in PLA and PAA experienced between the four players differed with each contact event category and role that the players performed. For example, median PLA was greatest for TG11 during tackles and collisions, but then the median PLA experienced by TG11 during rucks was the lowest of all four players. Likewise, TG20 and TG14 experienced statistically similar PAA magnitudes during tackles where they were the ballcarrier (98.14 rad/s^2, $p = 0.332$) but then their experience of PAA as the tackler differed significantly (541.34 rad/s^2, $p < 0.001$). No clear trend could be identified between the four example players of G6 concerning PLA or PAA across multiple contact events.

It was indicated that ranking players by their position groups in terms of PLA, PAA and frequency was sometimes misleading. The best example of this was highlighted by the significant differences observed in PLA and PAA between fullbacks and wings, and difference in PAA and frequency observed between fly-halves and scrum-halves. These four positions occupy two position groups and are objectively similar in body composition and player role. These observations imply that there is limited merit in macro grouping players by physical characteristics or match roles, for example, forwards and backs, front row players, and back three players due to the intra-group variation that has been observed in the data. Another interpretation could be that the positional groups should not be constructed by physical characteristics or traditional match roles as outlined in previous studies but should be grouped on an individual contact event involvement basis. For example, after monitoring a cohort of players for a set period of time, players could be grouped by contact event frequency rather than standard rugby union player groupings.

In terms of magnitude and frequency, it could be suggested that to reduce cumulative exposure to head acceleration, it is more favourable to play as a back than a forward. The only anomaly from this is from loosehead props. Overall, locks, tightheads, flankers and number eights have combined ranks far lower than any of the other positions indicating that these positions have high PLA, PAA and high frequency, which highlights these positions with the potential for high cumulative exposure to head acceleration over a season or career. Trying to relate the findings of this studies with previously published research was very challenging due to the paucity of head acceleration data published split beyond forwards and backs. Even finding contact event frequency and mTBI or subconcussive related injury frequency split by position subgroups was difficult. This highlights the benefit that this study could have on the research field. Players and coaching staff will be able to apply this research to their own matches or playing cohort and understand which player positions are more likely to be at risk of head acceleration accumulation and therefore, can be managed appropriately.

6.5. Link to the next chapter

Chapter 6 has highlighted the inter player group and intra position variation in the experience of contact event frequency, PLA and PAA. The key findings have outlined some trends in head acceleration exposure between player groups, however, differences between positions within certain player groups, in addition to variation between players who play the same position highlight the necessity for an individualised approach to monitoring head acceleration events. Chapter 4 underlined the variation of head acceleration exposure experienced during different contact events, Chapter 5 emphasized the similarities in head acceleration exposure during the top tiers of professional rugby union in England, and Chapter 6 alluded to the requisite need for an individual approach to head acceleration monitoring. A summary of key findings of this thesis is outlined in Chapter 7.

Chapter 7

Thesis Overview, Key Findings and Recommendations for Future Research

'It was my science that drove me to the conclusion that the world is much more complicated than can be explained by science.'

- Dr Allan Sandage. Astronomer. California Institute of Technology, USA. b. 1926 - d. 2010.

'People do not like to think. If one thinks, one must reach conclusions. Conclusions are not always pleasant.'

- Helen Keller. Author, Activist and Lecturer. b.1880 - d.1968.

7.1. Thesis Overview

This thesis aimed to be the summation of the collection and analysis of two seasons worth of head acceleration telemetry data using a cohort of professional rugby union players. At the time of writing, a prospective research study that assessed linear and angular head acceleration during rugby union matches conducted over multiple seasons, involving all player positions, did not exist. In total, over 2TB of impact signal data was recorded and combined with in excess of 100 hours of video footage from the matches. Over 70 different players were involved in the study with professional careers ranging from 0 to 13 years in length. The volume of data collected has made a considerable contribution to the development of this highly relevant and contentious research field and the novelty of this research cannot be understated.

Of the novel research chapters, Chapter 2 outlined the methods used throughout this thesis, highlighting the two seasons of head acceleration telemetry data collected using externally mounted telemetry units which had the ability to assess linear and angular head acceleration. Players wore the ITUs for all home fixtures irrespective of position or whether a member of the starting lineup or a substitute. The first season of data collection occurred during the 2019/2020 RFU Greene King Championship collating 11 matches of head acceleration telemetry data before the *COVID-19* pandemic prematurely ended the season. The second season of data collection during the 2020/2021 Gallagher Premiership season added a further 11 matches to the dataset. The head acceleration events were then tagged and labelled using a bespoke video analysis tool that allowed each telemetry trace to be attributed to a specific contact event category. In addition to the main dataset, Chapter 3 outlined a secondary study focussed on a small cohort of retired professional, semi-professional, and amateur rugby union players completing common rugby union contact events in a controlled environment. The purpose of the study was to allow for the characterisation of head acceleration telemetry during the common contact events where exact temporal markers could be applied to the beginning and end of the contact event.

Chapter 4 represented the macro-analysis of the contact and collision events from the Premiership and Championship head acceleration telemetry data. Tackles were the modal contact event, resulting in 3774 validated tackle events. Rucks were the second most common contact event with 2783 validated events. Lineouts, scrums, mauls and collisions were found to significantly contribute to the cumulative head acceleration that players were exposed to during seasons. Chapter 5 highlighted the differences in experience of head acceleration magnitude and frequency between the Premiership and Championship seasons indicating significantly higher exposure to PLA and PAA during the Premiership season. Even though the contact event head acceleration magnitude was higher during the Premiership season, contact event frequency was higher during the Championship season. Chapter 6 analysed the positional and player group differences regarding frequency and magnitude of head acceleration events across both seasons. Similarly to previously published research, Chapter 6 indicated that forwards were involved in more contact events and exposed to a higher magnitude of linear and angular acceleration when compared to backs. G2 players (second row) had the highest median PLA and second highest median PAA during contact events placing first overall in position group combined head acceleration rank. In contrast, G4 players (half-backs) had the lowest median PLA and second lowest median PAA during contact events placing sixth overall in position group combined head acceleration rank.

7.1.1. Research Questions

This thesis aimed to investigate the following:

1. Quantify the linear and angular head acceleration during major contact and collision events including tackle, ruck, scrum, maul, and lineout. (*Chapter 3 and Chapter 4*)
2. Outline any variation in linear and angular head acceleration when contact event role, collision orientation or collision height (where applicable) are altered. (*Chapter 3, Chapter 4 and Chapter 6*)
3. Highlight the difference in exposure to linear and angular head acceleration during tier one (Premiership) and tier two (Championship) matches. (*Chapter 5*)
4. Indicate any differences in linear and angular head acceleration and contact event involvement between player groups and player positions. (*Chapter 6*)

7.2. Summary of Key Findings

In terms of notable differences between contact events, it was clearly observed that tackles and rucks contribute the most events to a player’s cumulative subconcussive contact load during matches. However, the contribution of the more minor, and understudied contact events to a player’s accumulated subconcussive load should not be overlooked. Using scrum events as an example, 869 validated HAEs were recorded associated with scrum events, with a per event median PLA exposure of 11.13g and median PAA of 4395.08 rad/s^2 contributing to the cumulative subconcussive load of forward players. Mauls and lineouts also contributed a combined event frequency of approximately 1700 validated contact events. In addition to this, spurious collisions not associated with traditional contact events contributed in excess of 2000 validated HAEs.

As a general theme throughout this thesis, it was often difficult to consistently differentiate between the linear and angular head acceleration experienced during different contact events. Statistical differences between the magnitude of head accelerations experienced during different contact events did occur but potentially not in the volume that was predicted prior to this research being conducted. This could be due to several factors; primarily, there could just be a lack of detectable difference in the PLA and PAA exposure during rugby union contact events. Secondly, this lack of difference could be a result of statistical distortion caused by the large volume of contact events sampled. Only when the contact events were broken down into roles, orientations and heights (where appropriate) did more statistically significant results begin to appear. For example, one of the most notable findings from this thesis was the indication of the variation in exposure to linear and angular head acceleration experienced by tacklers versus ballcarriers. When a legal tackle occurred, as defined by World Rugby, tacklers experienced higher magnitudes of linear head acceleration, whereas ballcarriers tended to experience higher magnitudes of angular head acceleration. At the time of writing, this was a novel finding of this thesis and yet to be outlined in published research. However, the ideas surrounding a higher magnitude of PLA for the tackler are similar to the findings of other novel IMG published work (Roe et al., 2024). In reference to tackle height, there were themes that were consistent with previously published research, for example, statistically significant differences were found between the magnitude of PLA and PAA observed when point of collision during contact events was above the shoulder when compared with events where point of collision was lower than the shoulder. This was similar to recent IMG research which highlighted the similarities in magnitude between contact events when the PLA was greater than 40g (Sawczuk et al., 2024).

A secondary key finding was the relevance of player position or position group in dictating player exposure to linear and angular head acceleration. Forwards usually had a higher contact event frequency and magnitude than backs but there were some notable exceptions. G2 (second row) and G3 (back row) had the highest per contact event linear and angular head acceleration magnitude. In contrast, G4 (half-backs) had the lowest frequency and lowest contact event head acceleration magnitude rank. However, as previously mentioned, there was some notable intra player group variation. TG14 and TG73, both players in G5, had notably higher median PAA when compared with the other members of their player group. TG14 also had significantly higher contact event frequency than the other members of his group potentially suggesting that although the general trend indicates one proposal, individual technique and playing style can also have an impact on the exposure to HAEs during matches. In terms of player positions, tighthead props, locks, number eights and flankers had the highest PLA and PAA median magnitudes. For backs, fullbacks had the highest PLA magnitude and centres had the highest PAA magnitude. Somewhat expectedly, on average fly-halves were involved in the most contact events per match of any other back position potentially due to their propensity to handle the ball as fly-halves are often considered the first receivers after rucks and set pieces have been completed.

The idea of control in the contact area dictating experience of head acceleration was also proposed as a novel finding. The player initiating the contact, for example, the tackler during tackle events, often can dictate the ballcarrier’s experience of angular head acceleration and their own experience of linear head acceleration. By increasing the tackle height, ballcarrier

PAA increased to the point where contact above the shoulder was statistically significantly higher than other contact heights. In contrast, where ballcarriers reduced their height, or dipped into the tackle, this placed both ballcarrier and tackler at increased risk of greater magnitude of head acceleration. This finding supports the idea that mitigation against excessive exposure to head acceleration is the responsibility of all players involved in the contact event rather than the current onus placed upon certain roles, for example, the tackler, during contact events. Similar ideas around control of contact were proposed regarding ruck events. A clear-out type ruck would consider the attacking player as controlling the contact area, whereas the counter-ruck places the onus of control of the contact area on the defender. No statistically significant differences in PLA or PAA were identified between players performing these roles potentially indicating a similarity in mechanism. The greatest head accelerations during rucks often occurred after players were “off their feet” and so no longer in control of their bodies.

The difference between tier one and tier two of the English professional rugby union was characterised by higher magnitudes of PLA and PAA observed during tier one matches but higher frequency of contact events observed during tier two matches. Findings indicated that the modal role for the player cohort when involved in tackle events during the Premiership season was as the tackler. As tackle events dominated the contact event landscape during both seasons, and tacklers were often exposed to slightly, but not significantly higher magnitudes of PLA utilisation of the large sample could be enough to cause the significant differences observed between head acceleration exposure across both seasons. PLA for the minor contact events appeared to be higher during the Premiership season whereas, PAA for the minor contact events was observed to be higher during the Championship. The proposed explanation of this phenomenon was based upon the time in possession of the ball. During contact events, linear head acceleration tended to be greater when initiating contact as a defending player. In contrast, angular head acceleration was higher when the player had limited control of the contact event. Although not proven to be of any statistical relevance, the match win rate was higher in the Championship season and therefore, increased ball possession could be inferred. Therefore, leading to the increase in attacking roles such as ballcarrier, during contact events resulting in higher angular head acceleration.

For a professional rugby union player, there is no way to avoid exposure to head acceleration events. The identification of 2212 validated HAEs associated with collision events not specified as another type of contact event is enough to indicate that even when not involved in match play, the players will nonetheless be exposed to head acceleration. Nevertheless, there appear to be ways to potentially managed exposure based on position and contact event technique selection. If a player wishes to limit their exposure to subconcussive head acceleration, selection of player position would make the biggest contribution. The findings of this thesis indicate that transitioning from playing as a forward to playing as a back would be the most optimal change to reduce frequency and magnitude of exposure to subconcussive head accelerations. Beyond this transition, adaptations to tackle technique, for example, avoiding front orientated tackles and reducing propensity of tackles where contact height is above the chest would further reduce potential for high head acceleration magnitude. Head position in the ruck could also be a key consideration, although the findings of this thesis did not clearly identify, with any level of confidence, the optimal ruck technique. Overall, rugby union is a contact and collision sport, and as a result, the players are exposed to hundreds of subconcussive events per match of varying magnitudes.

From a summary perspective, notwithstanding the multitudes of statistical tests that were conducted on the large volume of data collected in this study, several of the key findings from each chapter cast aspersions based on tenuous claims from statistically significant tests. In reality, live match play is incredibly uncontrolled and making behavioural or mechanical recommendations based upon small differences in magnitude, be that statistically significant or not, could not be considered practical in the *real-world*. As has been highlighted in the earlier chapters of this thesis, the transition towards the use of IMGs as the primary method of collection of head acceleration data in rugby union during the completion of these studies has resulted in the validity of externally mounted IMUs being placed in doubt. However, Chapter 2 highlighted the multiple validation studies and published papers that relied entirely on phybrata units, Protxx IMU or X2 biosystems skin patch. If the reader of this thesis considers the measurements of the IMUs to be inaccurate, then the data collected in these studies would not be comparable to previously published literature or literature that using an alternate measurement device. This does not prevent the data and key findings to be internally comparable and a reflection of how different contact events, positions, orientations and roles differ in magnitude from each other within the confines of this study. Therefore, the key findings presented could be considered applicable to the wider research field or a representation of key indicators of events where further research would be required with a device where the reader has full confidence in its measurement validity.

7.3. Thesis Limitations

ITU Linear and Angular Sampling Thresholds

The most significant limitation in the scope of this thesis was the upper thresholds in linear and angular accelerations recording ability applied to the ITUs by the manufacturer. The research team was not made aware of these thresholds prior to acquisition of the ITUs and the thresholds were only discovered once data collection had begun. This limited the ability to collect the upper range of head accelerations that have been suggested in some previous research. However, due to the direction of the study, head acceleration magnitudes that have clear concussive potential were not the focus of this thesis. A counter argument to this mitigation could potentially be that due to the lack of conclusive evidence suggesting a magnitude to define the difference between a subconcussive head acceleration threshold as opposed to a mTBI threshold it would be difficult to suggest with any confidence that the limitations in recording ability of the ITUs did not also limit the collection of HAEs that were subconcussive in nature.

COVID-19 Disruption

As highlighted in Chapter 3, the *COVID-19* pandemic caused an unprecedented level of disruption to this study. Data collection was reduced to a single stream of data, head acceleration telemetry, with collection of visual cognitive screening data and blood biomarkers of trauma removed from this thesis due to lack of presentable data. The restrictions placed on social mixing and the introduction of "bubbles" prevented from full seasons of data being collected in either season. There was the intention to record head acceleration during training sessions throughout both seasons of data collection. Training sessions were recorded during the first half of the Championship season but were then not recorded during the Premiership season due to *COVID-19* restrictions. Ultimately, this did not mean a significant loss of data, due to the restrictions put in place resulting in training sessions during the research period being largely non-contact in line with government guidance. In addition to the aforementioned issues, in Chapter 4, the sample size used in the pilot study was also greatly reduced due to several positive *COVID-19* test results on the day of data collection.

Logistical Limitations

There were several logistical limitations that imposed assumptions upon the interpretation of the findings of this thesis. For example, only home fixtures were collected during both seasons resulting in only a small insight into the cumulative match load across a season due to the absence of data from fixtures played away. The option to exclude matches played away was an ethical consideration. Following advice from the head of athletic performance at the rugby club, the suggestion that the time frame for players to prepare themselves is shorter when playing away was made. Therefore, to ensure the players were adequately prepared for the matches, it was agreed that the application of ITUs was an unnecessary addition. To suggest that the data collected was indicative of a full season requires the assumption that the experience of head acceleration would be consistent at home and away fixtures.

There is notable reference to cumulative subconcussive load throughout this thesis without reference to training sessions. Head acceleration data was collected during training sessions in the first season of data collection. However, due to the *COVID-19* pandemic, head acceleration monitoring during training sessions was not conducted during the second season of data collection. Without training session head acceleration data, there is an increase in the assumptions surrounding the discussions of seasonal subconcussive cumulative load. Ultimately, this was not considered detrimental to the study due to limitations placed by the RFU on contact training time allowed by professional clubs during seasons therefore resulting in the contact time becoming inconsequential.

7.4. Direction of Future Research

Currently, the most significant issue with mTBI in sport research is the lack of objective, quantifiable methods to assess head injury. Knowing the magnitude and/or frequency of contact and collision events during matches and training does not provide the information required to conduct head injury assessments due to the lack of knowledge around subconcussive and concussive thresholds. The use or identification of biomarkers of neurotrauma associated with the certain magnitudes of head acceleration exposure during different contact events and matches would begin the process of quantifying the linear or angular acceleration required to begin the process of neurodegeneration.

There is the potential that a single cohort of professional rugby union players is not indicative of the wider population of rugby union players. The players who participated in this thesis were a diverse range of positions, ages and career lengths. However, a larger study containing more players from the top tiers of professional English rugby union might be a more effective way of expecting the understanding of subconcussive head accelerations. Another approach that could potentially be considered is by conducting a longitudinal study or a prospective study over an extended number of seasons to assess if there is any inter-season variation.

In majority of published research and mentioned regularly throughout this thesis, reference regarding head acceleration is often made to peak linear, or peak angular acceleration traditionally due to head acceleration event research directed towards concussive incidents. It has been suggested in this thesis that the potential for neurodegeneration is based upon the accumulation of head acceleration events, majority of which would be considered subconcussive. The accumulation of subconcussive head acceleration events over a career relating to the potential for neurodegenerative diseases is not a novel finding and has been suggested in previously published research. However, to effectively managed player cohorts, it could be suggested that an increased awareness of true subconcussive load is more important to majority of players, as opposed to the current intensive focus on events with concussive potential.

It is a suggestion from the findings of this thesis that a greater emphasis in the research field should be placed on the investigation and management of subconcussive load relating to presence of biomarkers of neurodegenerative diseases. In addition to providing quantifiable indications of neurotrauma, blood biomarkers can also be used as indicators of oxidative stress and inflammation. Markers of inflammation and oxidative stress aligned with head acceleration telemetry could provide further quantification of subconcussive injury. Summarily, the combination of multiple streams of data and the accumulation of more seasons of head acceleration data aligned with blood biomarker data could potentially alleviate some of the subjectivity that currently surrounds head injury in sport. The lack of quantification and lack of knowledge surrounding head acceleration thresholds that relate to a head acceleration being inconsequential, a subconcussive head acceleration or a concussive head acceleration essentially negate any consistency in head injury management. To quantify the topic further, there needs to be research conducted that can associate subconcussion or true mTBI events with presence of biomarkers of neurotrauma, biomarkers of oxidative stress, or changes in neurological structures.

7.5. Conclusive Statement

Rugby union is contact and collision sport, and subsequently the propensity for any individual who chooses to participate in such a sport must be aware that head acceleration events with the potential to be subconcussive or concussive do occur. The studies within this thesis have highlighted certain contact events, player groups and player roles where frequency or magnitude of head acceleration is significantly increased. A step in the right direction for the future success of rugby union and the enhancement of player welfare would be to consider the high exposure players contained within this thesis, and design management and training strategies to limit their exposure to head acceleration. The idea that high exposure events and roles can be totally avoided is fanciful, but the interpretation of data presented, including statistical test may require more than a purely literal translation. For example, statistical significance does not always imply *real-world* attributable difference when the magnitude of the head acceleration is so similar between different contact events. Ultimately, exposure to subconcussive head acceleration events over an extended period of time will only be a detriment to the long-term health of the players. It is the combined responsibility of players, coaches, legislators, and medical professionals to ensure the priority is player health and well-being beyond that of competition success. However, the required changes may not be possible to implement with the current cohort of professional rugby union players. Implementation of behavioural and mechanical that are so deeply imbedded in the mannerisms of current professional players will be difficult to change and so a focus on changing the contact mechanics and techniques of the youth or academy cohorts may be a more successful method of securing the longevity of rugby union and ensuring the welfare of future generations.

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Appendices

Appendix A: Consent Form

Project title: *Multi-source evaluation of concussion and sub-concussive head accelerations in elite male rugby union players*

Researcher(s): **Mr Thomas Goodbourn,** Dr Karen Hind, Mr Jonathan Frawley, **OMITTED**, Dr Paul Chazot, Dr Lisa Macbeth, Dr Doug King, Dr Joe Nevin and Dr Michelle Swainson.

Department: Sport and Exercise Sciences
Contact details: thomas.a.goodbourn@durham.ac.uk
Supervisor name: Dr Karen Hind
Supervisor contact details: karen.hind@durham.ac.uk

This form is to confirm that you understand what the purposes of the project, what is involved and that you are happy to take part. Please initial each box to indicate your agreement:

I confirm that I have read and understand the Information Sheet dated [] and the Privacy Notice for the above project.	
I have had sufficient time to consider the information and ask any questions I might have, and I am satisfied with the answers I have been given.	
I understand who will have access to provided personal data, how the data will be stored and what will happen to the data at the end of the project.	
I agree to follow the Covid-secure protocols in place at the club.	
I agree to take part in the above project, including; 1. Providing up to four blood samples upon request, 2. Wearing of Protxx sensors during contact training sessions and games, 3. Completing a visual/cognitive skills assessment test (King-Devick Test), 4. Review of contact events including, but not exclusively: tackles, rucks, mauls and scrums by the research team, 5. Completing three repeats of an isometric neck strength test (pre-season, mid-season and post-season).	
I understand that my participation is entirely voluntary and that I am free to withdraw at any time without giving a reason.	

Participant's Signature________________________________ Date______________

(NAME IN BLOCK LETTERS)____

Researcher's Signature_______________________________ Date______________

(NAME IN BLOCK LETTERS)____

Durham University

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Appendix B: Participant Information Sheet

(V2: September 2020)

You are invited to take part in a research project. Before you decide if you would like to take part, please read this information sheet carefully. You can also ask the lead researcher, Thomas Goodbourn, if you have any questions (please see contact details at the end of this sheet).

Title of Project: *Multi-source evaluation of concussion and sub-concussive head accelerations in elite male rugby union players.*

What is the purpose of the research?

The purpose of this study is to measure head impact forces during contact training sessions and matches. The research is important to improve understanding of the risks and to lead to the development or improvement of strategies to protect player health and welfare.

Why have I been invited to take part?

You have been invited to take part in this study because you are a professional rugby player aged between 18 and 40 years.

Do I have to take part?

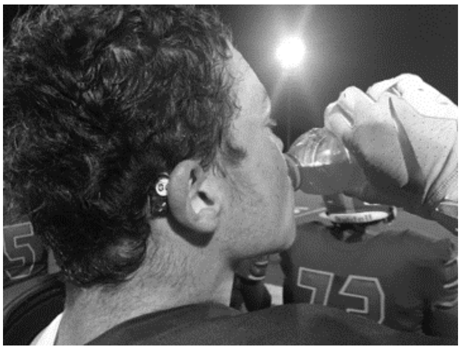
You do not have to participate in the project. You can request withdrawal of your data until data analysis is complete and ready for publication. You have the right to request the withdrawal of your identifiable data at any time.

What will be involved if I decide to take part in the research?

The testing includes head impact monitoring using head-mounted sensors, blood sample collection and analysis and simple visual screening tests.

Head Impact Sensors

If you choose to take part in the study, you may be asked to wear the Protxx head impact sensors at each contact training session and / or at all home matches that you are selected for. The image below indicates the positioning and size of the sensors:



When asked to wear the sensor it will be positioned for you by the researcher or an athletic trainer. It is important that if the sensor becomes dislodged at any point, that you inform the researcher at the earliest opportunity so that the sensor can be repositioned. The data collected will be transferred from the sensor to the software on an iPad using Bluetooth technology. The data will inform on number of impacts, type of impact (linear or rotational) and force of impact (measured in g-force).

Blood Analysis

Up to four samples of blood will be taken for analysis by a GMC registered medical doctor. Blood sampling will take place at the end of pre-season, mid-season and end of season. All samples will take place in a private treatment room at **OMMITTED**. The samples will be analysed for markers of brain health.

Visual Screening Test

The visual screening test that will be used is the King-Devick tool. The K-D test is a two-minute rapid number-naming assessment where you will be asked to read out-loud three cards (shown on an iPad), with a series of numbers on as fast as possible. This test gives a good indication of eye and language function, in addition to impairment of attentional focus.

GPS Data

Workload and heart rate data will be collected via your usual GPS devices and heart rate monitors. This will be used to identify whether there is any association between fatigue and head impact force.

Video Analysis

Impacts will be analysed using video analysis to support identification of techniques and events leading to more or less significant head impacts. There will be no additional filming taking place outside of the usual camera presence.

Isometric Neck Strength Test

The neck strength test will involve you wearing a head strap and pulling against a handheld testing device. You will be asked to pull forward, backwards and to each side against the testing device. These tests will be completed during preseason, at a mid-season point and at the end of the season. This test will potentially indicate association between neck strength and head impact force.

What are the benefits and risks of taking part?

The benefits of taking part in this research are to contribute to advancing the knowledge in sport-related concussion assessment and it is hoped that the findings will help inform current practice of concussion management. You will be provided with your results if you wish.

The risks of taking part are few outside of your normal professional rugby activities. There is a small risk associated with blood sampling in that you may feel a small scratch and there is a low risk for bruising, however the risks associated with blood sampling will be minimised by the medical doctor who has significant experience and expertise.

What steps are being taken to mitigate the risk of COVID-19?

All government, university, **OMMITTED** and RFU guidelines regarding COVID-19 will be adhered to at all times. 2m social distancing will be observed, where possible, and all sensors will be sanitized after use to prevent cross-contamination. The attachment and removal of the impact sensors, and the King Devick test, will be carried out by **OMMITTED** or a member of the backroom staff team. The blood sampling will be performed by a medic who will wear a medical grade face covering and disposable medical gloves. You are asked to follow the rugby club guidelines with regard to reducing the risk of Covid-19 at testing, training and on match days, and if you need any further information on the rugby club guidance and risk assessment, please contact **OMMITTED**.

How will confidentiality be assured?

Your data will be anonymised using codes, and prior to data analysis all data will be held securely on a password protected computer/laptop and will not be shared outside of the research team. No personal data will be shared, and you will not be identified in any resultant outputs such as the student thesis or publications. If you consent, your weekly impact data will be shared with the coaching/medical staff. Please see the Privacy Notice for further details.

What will happen to the results of the research?

The results of the research will be presented in a PhD thesis submitted to the Department of Sport and Exercise Sciences at Durham University, conference presentations and published research papers. No names (including club name) will be used in any output.

If you have any questions related to the project, please contact the lead researchers:

Thomas Goodbourn
Email: thomas.a.goodbourn@durham.ac.uk
Supervisor Name: Dr Karen Hind
Address: 42 Old Elvet, Durham, DH1 3HN
Email address: karen.hind@durham.ac.uk

If you are happy with the answers to your questions, please complete and sign the enclosed Informed Consent Form.

Appendix C: Privacy Notice

Durham University has a responsibility under data protection legislation to provide individuals with information about how we process their personal data. We do this in a number of ways, one of which is the publication of privacy notices. Organisations variously call them a privacy statement, a fair processing notice or a privacy policy.

To ensure that we process your personal data fairly and lawfully we are required to inform you:

- Why we collect your data
- How it will be used
- Who it will be shared with

We will also explain what rights you have to control how we use your information and how to inform us about your wishes. Durham University will make the Privacy Notice available via the website and at the point we request personal data.

Our privacy notices comprise two parts – a generic part (ie common to all of our privacy notices) and a part tailored to the specific processing activity being undertaken.

Data Controller

The Data Controller is Durham University. If you would like more information about how the University uses your personal data, please see the University's Information Governance webpages or contact Information Governance Unit:

Telephone: **OMMITTED**

E-mail: **OMMITTED**

Information Governance Unit also coordinate response to individuals asserting their rights under the legislation. Please contact the Unit in the first instance.

Data Protection Officer

The Data Protection Officer is responsible for advising the University on compliance with Data Protection legislation and monitoring its performance against it. If you have any concerns regarding the way in which the University is processing your personal data, please contact the Data Protection Officer:

OMMITTED

Your rights in relation to your personal data

You have the right to be provided with information about how and why we process your personal data. Where you have the choice to determine how your personal data will be used, we will ask you for consent. Where you do not have a choice (for example, where we have a legal obligation to process the personal data), we will provide you with a privacy notice. A privacy notice is a verbal or written statement that explains how we use personal data.

Whenever you give your consent for the processing of your personal data, you receive the right to withdraw that consent at any time. Where withdrawal of consent will have an impact on the services we are able to provide, this will be explained to you, so that you can determine whether it is the right decision for you.

Accessing your personal data

You have the right to be told whether we are processing your personal data and, if so, to be given a copy of it. This is known as the right of subject access. You can find out more about this right on the University's Subject Access Requests (SAR) webpage.

Right to rectification

If you believe that personal data we hold about you is inaccurate, please contact us and we will investigate. You can also request that we complete any incomplete data.

Once we have determined what we are going to do, we will contact you to let you know.

Right to erasure

You can ask us to erase your personal data in any of the following circumstances:

- We no longer need the personal data for the purpose it was originally collected.
- You withdraw your consent and there is no other legal basis for the processing.
- You object to the processing and there are no overriding legitimate grounds for the processing.
- The personal data have been unlawfully processed.
- The personal data have to be erased for compliance with a legal obligation.
- The personal data have been collected in relation to the offer of information society services (information society services are online services such as banking or social media sites).

Once we have determined whether we will erase the personal data, we will contact you to let you know.

Right to restriction of processing

You can ask us to restrict the processing of your personal data in the following circumstances:

- You believe that the data is inaccurate, and you want us to restrict processing until we determine whether it is indeed inaccurate.
- The processing is unlawful, and you want us to restrict processing rather than erase it.
- We no longer need the data for the purpose we originally collected it, but you need it in order to establish, exercise or defend a legal claim and,
- You have objected to the processing and you want us to restrict processing until we determine whether our legitimate interests in processing the data override your objection.

Once we have determined how we propose to restrict processing of the data, we will contact you to discuss and, where possible, agree this with you.

Retention

The University keeps personal data for as long as it is needed for the purpose for which it was originally collected. Most of these time periods are set out in the University Records Retention Schedule.

Making a complaint

If you are unsatisfied with the way in which we process your personal data, we ask that you let us know so that we can try and put things right. If we are not able to resolve issues to your satisfaction, you can refer the matter to the Information Commissioner's Office (ICO). The ICO can be contacted at:

Information Commissioner's Office Wycliffe House Water Lane Wilmslow Cheshire SK9 5AF

Telephone:*OMMITTED*

Appendix D: Tailored Privacy Notice

Project Title: *Multi-source evaluation of concussion and sub-concussive head accelerations in elite male rugby union players.*

This section of the Privacy Notice provides you with information that you need to know before you provide personal data to the University for the particular purpose(s) stated below.

Type(s) of personal data collected and held by the researcher and method of collection:

Personal data will be collected through the process of obtaining consent, including your age, gender, job type, number of years playing professional rugby and physical data (body composition, workload data e.g. heart rate and GPS).

Video footage of training and matches will also be collected. At no point will individuals be identified/footage shared in thesis, publication or for any other means outside of the members of the named research team.

Lawful Basis

Collection and use of personal data is carried out under the University's public task, which includes teaching, learning and research.

How personal data is stored:

All personal data will be held securely and strictly confidential to the research team. Data in electronic form will be stored on a password-protected computer. Hardcopies (e.g., consent forms) will be scanned electronically and shredded. Data will not be available to anyone outside the research team. All video recordings will be stored in password-protected files and shared only via encrypted communications.

How personal data is processed:

Identifiable data will be kept separate from data analysis spreadsheets, you will be assigned a participant code for data analysis.

Withdrawal of data

You can request withdrawal of your data until data analysis is complete and ready for publication. You have the right to request the withdrawal of your identifiable data at any time.

Who the researcher shares personal data with:

The only individual with access to identifiable data will be the named researchers.

How long personal data is held by the researcher:

All data from this research, including the consent form, containing your personal identifiable data will be held from the end of the project for 10 years.

How to object to the processing of your personal data for this project:

If you have any concerns regarding the processing of your personal data, or you wish to withdraw your data from the project, please contact the researcher, **OMMITTED** in the first instance.

If you are unsatisfied, or to raise any concerns, please contact **OMMITTED**, Head of Department of Sport and Exercise Sciences, Durham University **OMMITTED**.

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Appendix E: Durham University Data Management Plan

Summary Information

Lead Academic at Durham:	Mr Thomas Goodbourn (PhD student), Dr Karen Hind (supervisor (DSES)), Mr Jonathan Frawley (supervisor (ARC)) and Dr Paul Chazot (supervisor (Biosciences))
Project Title:	*Multi-source evaluation of concussion and sub-concussive head accelerations in elite male rugby union players*
Start and End Dates:	Start Date = 01.08.2019 End Date = 30.09.2023
Funder:	-
Date Plan Completed:	
Version:	1.0

Details	
1. Describe the data to be generated by the project	*Data gathered in the project can be split into two different areas; blood data and non-blood data. Blood data will consist of the recordings of the analysis following the blood plasma being removed from the four sample periods. Non-blood data will include all the recordings of the twenty-four sensors for contact training sessions and games, video analysis, GPS tracking, isometric neck strength data and visual/cognitive assessment data, which will be a significantly larger collection of raw data than with the blood analysis.*
2. How much data do you expect to produce?	*Less than 4TB*
3. Will the data be governed by any ethical or legal considerations? If yes, please describe	*Personal identifiable data, including video analysis, will not be shared outside of the research team. This data will be password protected and video files will be encrypted. Video files will be*

	*review in a private location in personal premises, DSES or *OMMITTED*.* *Data held in spreadsheets are fully anonymised using codes.* *Consent provided by the participants includes the collection and analysis of physical data (including blood tissue) and that data will be anonymised for analysis.* *The storage and analysis of the serum blood samples are exempt from the Human Tissue Act.*
4. Describe the roles and responsibilities of the project team in relation to data management.	*Thomas Goodbourn PGR student, Department of Sport and Exercise Sciences has overall responsibility and with his supervisor Dr Karen Hind. Dr Paul Chazot, Department of Biosciences, will have main responsibility of the blood serum sample storage.* *All other non-blood data will be held and analysed at Durham University under the responsibility of Thomas Goodbourn and Dr Karen Hind.*
5. How will active data be organised and stored during the life of the project?	*All data for analysis will be anonymised.* *Serum samples will be stored in a -80 degree freezer in the Dept of Biosciences under the responsibility of co-investigator, Dr Paul Chazot. Sample aliquots will be coded.* *Data is stored on password protected PC and backed up using encrypted hard drives.*
6. How will you access and share data during the project?	*As above.* *Named collaborators and potentially Durham University students (at the decision of Dr Hind), will have access to anonymised data only.*
7. What are the arrangements for long term storage and preservation of data?	*All data will be archived electronically under the responsibility of Dr Karen Hind, password protected and at Durham University (University PC in locked room). If longitudinal or further study is planned, additional ethical approvals will be sought prior, and a new data management plan will be drawn.* *In the first instance, data will be kept for 10 years. If data is needed to be kept for a longer duration, approval will be sought.*
8. If you plan to make the final dataset available, what data sharing arrangements will be in place?	*The final data set will not contain any personal identifying information and will be fully anonymised.* *At this stage, data will not be shared outside of the research team.*

APPENDIX F: RISK ASSESSMENTS

Name of researcher(s):	Thomas Goodbourn
Email Address(es) of researcher(s):	thomas.a.goodbourn@durham.ac.uk
Project Title:	*Multi-source evaluation of concussion and sub-concussive head accelerations in elite male rugby union players*
Project Funder (where appropriate):	-
When do you intend to start data collection?	04/08/2019
When will the project finish?	September 2023
Student ID: Degree, year and module: Supervisor:	**OMMITTED** 2nd Year PGR (PhD) Student Dr Karen Hind, Mr Jonathan Frawley, Dr Paul Chazot

A) POTENTIAL RISKS TO PARTICIPANTS

What risks to participants may arise from participating in your research?	How likely is it that these risks will actually happen?	How much harm would be caused if this risk did occur?	What measures are you putting in place to ensure this does not happen (or that if it does, the impact on participants is reduced)?
Irritation from sensor adhesive Bruising from needles Psychology of being test – concern over why they are being tested	Low Medium Low	Low-Medium Low-Medium Medium-High	Medical team will identify any player allergies Experienced anaesthetist completing phlebotomy Education on what the testing involves through presentations and provision of info sheets to ensure players fully understand the person of the research

Media Interest	Low	Medium	Due to the highly topical nature of the research, the study may generate media attention. Players will be informed of this prior to involving themselves in the study.
Exposure to COVID-19	Low/Medium	Significant	See COVID-19 Risk Assessment and Rugby COVID-19 Assessment.

B) POTENTIAL RISKS TO RESEARCHERS

Research Site Location/Address: ***OMMITTED***

What hazards or risks to you as a researcher may arise from conducting this research?	How likely is it that these risks will actually happen?	How much harm would be caused if this risk did happen?	What measures are being put in place to ensure this does not happen (or that if it does, the impact on researchers is reduced)?
Exposure to sharps	Low	Significant	All phlebotomy will be performed by a GMC medic with COVID-19 secure training.
Exposure to COVID-19	Low/Medium	Significant	See COVID-19 Risk Assessment and Rugby COVID-19 Assessment.

Risk Assessment 2

Location(s): *(where will the activity or task take place?)*	**Description of task or Activity:** *(to include enough information to establish the foreseeable hazards)*
OMMITTED	**Application, wearing and removal of head impact sensors**

Hazards *(things with the potential to cause harm)*	**Those at risk** *(people who could be harmed)*	**How could they be harmed?** *(nature of injuries, damage that could result)*	**Uncontrolled risk level** *(level of risk without control)*	**Required controls** *(how the risk can be removed or reduced by for example engineered methods, safe systems of work, training and/ or personal protective equipment)*	**Controlled risk level** *(level of risk remaining when controls are in place)*
Adhesive used to attach head impact sensor to player (behind ear)	Participant	*There is a potential risk of allergic reaction to the adhesive*	**Moderate**	• The club sport science and medical team ensure that players are not allergic to the adhesive. • The adhesive (Mueller Tuffner *Pre-Tape*) is commonly used and designed for sport.	**Low**
Attaching and removing the head impact sensors - close contact between researcher and participant	Researcher and participant	*Risk of contracting/ spreading Covid-19*	**Moderate**	• The researcher will not be in close contact with the participants. The rugby club sport science/medical team will place and remove the sensors and follow the rugby club risk assessments. • Participants and staff will not be in attendance if they have symptoms of Covid-19 or have been in close contact with someone who has tested positive for Covid-19 within the last 14	**Low**

				days. Participants: • Are tested on a weekly basis by the rugby club • Have their temperature checked on arrival to the club stadium and are sent home if their temperature is elevated. • Follow guidance in the attached risk assessment prepared by the rugby club.	

Risk Assessment 3

Location(s): *(where will the activity or task take place?)*			**Description of task or Activity:** *(to include enough information to establish the foreseeable hazards)*		
OMMITTED			**Collection of venous blood samples using venipuncture**		
Hazards *(things with the potential to cause harm)*	**Those at risk** *(people who could be harmed)*	**How could they be harmed?** *(nature of injuries, damage that could result)*	**Uncontrolled risk level** *(level of risk without control)*	**Required controls** *(how the risk can be removed or reduced by for example engineered methods, safe systems of work, training and/ or personal protective equipment)*	**Controlled risk level** *(level of risk remaining when controls are in place)*
Collecting and preparing samples for analysis	Participant and researcher	*There is a risk of cross infection of blood borne virus/disease between the participant / researcher.*	**High**	**Implement the following safe systems of work:** A medic (NHS) or certified phlebotomist will carry out venipuncture and follow the agreed protocol as follows: • Use single-use, nitrate gloves, and gloves which must be changed after each participant. • Swab the skin where the sample will be taken from prior to each test. • Use only single-use sharps. • Ensure that all sharps are disposed into the sharps bin immediately after use. • Ensure that all gloves, swabs and tissues are disposed of immediately after the test, into the clinical waste bin. • Post sampling, advise the participant to press down on the site of insertion with cotton wool, until any bleeding (likely to be minor) stops. • Ensure that working surfaces and chair/bed are kept	**Low**

				clean and cleaned regularly before and after each participant, using the appropriate cleaning solutions.	
Venous blood sampling process	Participant	*There is a risk of injury to the site where the sample is taken.*	**High**	The researcher is competent and experienced.	**Low**
Venous sampling process	Participant	*There is a risk of injury to the participant should they faint during the sampling because of the sight of the needle or the local environment.*	**Moderate**	The researcher will ensure the participant is seated and supported. Instruct the participant to look aware if uneasy about the procedure. A chaperone/peer will be present.	**Low**
Blood sampling and handling	Researcher and participant, and other laboratory users	*Blood spillage brings a risk of infection /cross contamination.*	**Moderate**	Ensure access to a spillage cleaning kit at all times. The researcher must wear disposable, nitrate gloves when cleaning the spillage. The researcher must clean the spillage immediately and dispose of gloves and cleaning material in the clinical waste bin.	**Low**
Clinical and sharps waste	Researcher	*There is a potential risk of*	**Moderate**	The researcher: • Must be aware that the sharps must be disposed of	**Low**

handling		*cross infection.*		in the yellow sharps bin and not the clinical waste bin. • Must not remove full bagged clinical waste or the sharps bin, to the general bin. Clinical waste and sharps aste must be removed according to laboratory protocol. • Must remove any watch or jewelry to avoid these falling into the clinical waste bin or sharps bin. • Must not attempt to remove any item from the clinical waste or sharps bin.	
Close contact between researcher and participant	Researcher and participant	*Risk of contracting/ spreading Covid-19*	**Moderate**	The researcher: • Must wear a face covering at all times. • Must wear a new pair of disposable nitrate gloves for each participant. • Must not conduct the sampling if he/she has symptoms of Covid-19 or has been in close contact with someone who has tested positive for Covid-19 within the last 14 days. Participants: • Are tested on a weekly basis by the rugby club • Have their temperature checked on arrival to the club stadium and are sent home if their temperature is elevated. • Follow guidance in the attached risk assessment prepared by the rugby club.	**Low**

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Health and Safety Risk Matrix

			Probability/ likelihood of risk realisation				
			Almost Impossible (1)	Not Likely to occur (2)	Could occur (3)	Known to occur (4)	Common occurrence (5)
		Health and Safety	A freak combination of factors would be required for risk to be realised	A rare combination of factors would be required for risk to be realised	Could happen when additional factors are present otherwise unlikely to occur	Not certain to happen but an additional factor may result in risk being realised	Almost inevitable that risk will be realised
Potential Consequences	Severe (5)	One or more fatalities. Irreversible health problems	5	10	15	20	25
	Major (4)	Partial or medium-term, disabilities or major health problems	4	8	12	16	20
	Moderate (3)	Lost-time injuries or potential medium-term health problems	3	6	9	12	15
	Minor (2)	Minor, very short-term health concerns on recordable injury cases.	2	4	6	8	10
	Insignificant (1)	Inherently safe, unlikely to cause health problems or injuries	1	2	3	4	5

Extreme risk	High risk	Medium risk	Low risk

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COVID-19 Risk Assessment

Completed by: Mr Thomas Goodbourn
Date completed: 17/09/20

Action to be considered	Action taken (to be completed by researcher in association with participant gatekeeper)	Significance of risk (low, medium, high)
General guidance		
Ensure researchers have read and understood the RFU guidance on mitigating the risks of COVID-19	All researchers have already read the documents.	LOW
Ensure details of researchers have been shared with rugby club's COVID-19 officer and DSES COVID-19 officer	Details of all researchers that will come into contact with rugby club players and staff will be provided to the rugby club's COVID officer (**OMMITTED**) and DSES COVID officer (Mr Rob Cramb).	LOW
Ensure compliance with Test and Trace by keeping a register (including contact details) of those researchers present at training/matches. These registers should be held in line with the activity provider's data storage policy.	A data log to track exposure between researchers and participants including times and places will be created and regularly updated. This data log can be provided to the COVID officers upon request.	MEDIUM
Ensure all participants have signed the participant consent form prior to testing	The deadline for signing of participation consent form will be two days prior to first sampling day.	LOW
Ensure all participants are aware of all COVID-19 policies and processes in advance of testing	Regular updates will be provided to participants on which days will be test days. Participants are expected to adhere to all club, university and RFU guidelines regarding COVID-19 where applicable.	MEDIUM
Ensuring appropriate provisions in place to maintain	Separate provisions in place for each section. The rugby club has	HIGH

social distancing guidance and that participants are made aware of the policy in place around usage. This should include: timings, how participants enter and exit the pitch, any process/cleaning before etc.	already made provisions to ensure minimum possible exposure to COVID-19. In the stadium, one-way systems are in place, face-coverings are mandatory and social distancing guidelines are in place at all times for participants, researchers and staff. For further detail, please refer to the attached Rugby COVID-19 risk assessment. Timings: The researcher will provide details, agreed with the gatekeeper (**OMMITTED**), as to when and where testing will take place. Participants will be informed of this prior in their weekly team meetings. Processes/Cleaning: All researchers will sanitize on arrival and will wash hands/re-sanitize at regular intervals. All Protxx sensors will be sanitized before and after use to prevent cross contamination. Sensors will only be used a maximum of twice per week, with a minimum of 72 hours between test days. Sensor application will be completed by the gatekeeper under the supervisor of the lead researcher to limit participant exposure to external individuals. All blood sampling will be completed by GMC registered physician who has previous completed COVID secure training in association with their role in the NHS. When appropriate, the researchers will limit their proximity to participants and adhere to appropriate social distancing procedures.	
Handwashing facilities (including soap and water) are available. Alternatively (or additionally) provide	The rugby club has provided hand sanitizer and hand washing facilities around the stadium and this should be used at regular	LOW

sufficient hand sanitiser. Regular hand washing should be encouraged.	intervals. The researchers will also provide their own hand sanitizer and wear appropriate PPE to reduce the risk to participants and themselves.	
Ensure that disposable tissues/paper towels/anti-bacterial wipes are available to reduce the threat of transmission. Consider how these are disposed of following use e.g. sealed bins	Disinfectant wipes will be provided by the researchers for the cleaning of sensors. Also, disposable gloves, face coverings (FFP3) and face shields will be worn when in close proximity to participants.	LOW
Display of education pieces, such as a symptoms chart and handwashing guidance, to raise awareness and promote safe practices	The rugby club already provides relevant handwashing and other guidance posters around the stadium, clearly showing the correct procedures and relevant government advice.	LOW
Consider how to manage non-compliance with actions taken to manage the risks of COVID-19	The rugby club already has set out a disciplinary process to deal with non-compliance to the new COVID rules. Initial stages should focus on warnings and education around the procedures. Repeat offences must be dealt with seriously to keep other participants, staff and researchers safe and to discourage further transgressions.	LOW
Provisions in place to manage arrival/departure of individuals to/from the stadium	One-way system will be in place around the stadium. The rugby club staggers the arrival of different groups of participants (e.g. 1st team vs. academy) to reduce the number of people of site at any one time.	LOW
Testing Guidance		
Ensure Protxx sensors are cleaned and disinfected before and after use.	All Protxx sensors will be sanitized before and after use to prevent cross contamination. Sensors will only be used a maximum of twice per week, with a minimum of 72 hours between test days. Sensor application will be completed by the	MEDIUM

	gatekeeper under the supervisor of the lead researcher to limit participant exposure to external individuals.	
Ensure, where possible, limitation of sharing of equipment e.g. GPS devices, heart rate monitors	GPS and heart rate data is controlled and collected by the rugby club. All participants will be assigned a personal GPS device, GPS vest holder, heart rate monitor and strap which will remain the same for the duration of the season to reduce risk of COVID-19 exposure. All devices will be sanitized before and after use.	MEDIUM
No close physical contact (including hand shaking, huddles, sharing of water bottles etc.) in line with government guidance. This extends to pre, during and post-match meetings, briefings, de-briefs, half time talks, celebrations and any breaks in play.	All participants have been informed by the rugby club that unless playing in a match or training they will be required to socially distance as advised by the government guidelines.	LOW
Ensure appropriate First Aid provisions are accessible (**https://www.sja.org.uk/get-advice/first-aid-advice/covid-19-advice-for-first-aiders/)**	All first aid kits by the pitches will have a box of gloves and masks with them. First aid provision is covered by onsite doctors and physiotherapists at the rugby club.	LOW
Consider whether personal protective equipment (PPE) is required to safely conduct testing (Researchers, gatekeepers, etc.)	Researchers will all wear PPE (face coverings, face shields and disposable gloves) when at the stadium.	LOW
Ensure social distancing is maintained for substitutes, team staff, officials, spectators and during breaks in play.	All participants, staff and researchers will abide by social distancing rules as outlined by RFU, Durham University, the rugby club and national government guidelines.	LOW

Appendix G: Consent Form - Pilot Study

Project title: *In-vivo validation of head impact telemetry for the measurement of linear and angular acceleration in rugby union*

Researcher(s): **Mr Thomas Goodbourn,** Dr Karen Hind & Mr Jonathan Frawley
Department: Sport and Exercise Sciences
Contact details: thomas.a.goodbourn@durham.ac.uk
Supervisor name: Dr Karen Hind
Supervisor contact details: karen.hind@durham.ac.uk

This form is to confirm that you understand what the purposes of the project, what is involved and that you are happy to take part. Please initial each box to indicate your agreement:

I confirm that I have read and understand the Information Sheet and the Privacy Notice for the above project.	
I have had sufficient time to consider the information and ask any questions I might have, and I am satisfied with the answers I have been given.	
I understand who will have access to provided personal data, how the data will be stored and what will happen to the data at the end of the project.	
I agree to follow the Covid-secure protocols in place at the university.	
I agree to take part in the above project, including; 1. Wearing of Protxx sensors, GPS units & heart rate monitors during recording sessions, 2. Partaking in simulated contact drills considered similar to real rugby events, 3. Review of contact drills including, but not exclusively: tackles, rucks, mauls and scrums by the research team,	
I understand that my participation is entirely voluntary and that I am free to withdraw at any time without giving a reason.	

Participant's Signature_______________________________ Date______________

(NAME IN BLOCK LETTERS)____

Researcher's Signature______________________________ Date______________

(NAME IN BLOCK LETTERS)____

Appendix H: Participant Information Sheet - Pilot Study

You are invited to take part in a research project. Before you decide if you would like to take part, please read this information sheet carefully. You can also ask the lead researcher, Thomas Goodbourn, if you have any questions (please see contact details at the end of this sheet).

Title of Project: *In-vivo validation of head impact telemetry for the measurement of linear and angular acceleration in rugby union*

What is the purpose of the research?

The purpose of this method study is to simulate contact scenarios, in a controlled environment, to allow correct identification of head impact events from live match and training data. The research is important to improve understanding of the risks and to lead to the development or improvement of strategies to protect player health and welfare.

Why have I been invited to take part?

You have been invited to take part in this study because you are an experienced rugby player aged between 18 and 40 years.

Do I have to take part?

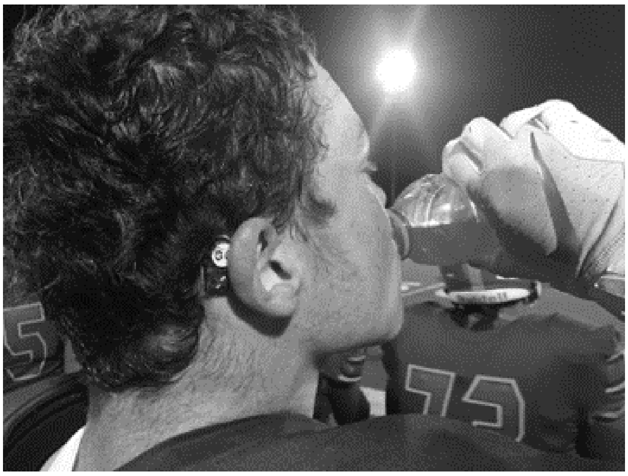
You do not have to participate in the project. You can request withdrawal of your data until data analysis is complete and ready for publication. You have the right to request the withdrawal of your identifiable data at any time.

What will be involved if I decide to take part in the research?

The testing includes head impact monitoring using head-mounted sensors, whilst partaking in several rugby scenarios to simulate match and training impacts.

Head Acceleration Sensors

If you choose to take part in the study, you may be asked to wear the Protxx head acceleration sensors at each recording session. The image below indicates the positioning and size of the sensors:



When asked to wear the sensor it will be positioned for you by the researcher. It is important that if the sensor becomes dislodged at any point, that you inform the researcher at the earliest opportunity so that the sensor can be repositioned. The data collected will be transferred from the sensor to the software on an iPad using Bluetooth technology. The data will inform on type of impact (linear or rotational) and force of impact (measured in g-force).

Contact Scenarios

1. Tackle – a selection of tackle scenarios including: tackles from front, side or behind; tackles of different heights on body; and double tackles. All scenarios will require you to be a tackler and ballcarrier.
2. Breakdown – a selection of breakdown scenarios including: different types of clear-out, jackles and counter rucks. Again, all scenarios will require you to partake as a offensive and defensive player in the breakdown.
3. Set Piece – a selection of simulated lineout, maul and scrum scenarios.
4. Changes of direction – a selection of dummies and fakes

Video Analysis

Impacts will be analysed using video analysis to support identification of techniques and events leading to more or less significant head impacts.

Other metrics

You will be requested to wear heart rate monitors and GPS as an indication of workload whilst partaking in the impact scenarios.

What are the benefits and risks of taking part?

The benefits of taking part in this research are to contribute to advancing the knowledge in sport-related concussion assessment and it is hoped that the findings will help inform current practice of concussion management. You will be provided with your results if you wish. The risks of taking part are few outside of your normal rugby activities.

What steps are being taken to mitigate the risk of COVID-19?

All government and university guidelines regarding COVID-19 will be adhered to at all times. 2m social distancing will be observed, where possible, and all sensors will be sanitized after use to prevent cross-contamination. The attachment and removal of the impact sensors will be carried out by lead researcher, Thomas Goodbourn. The lead researcher will wear a medical grade face covering and disposable medical gloves. You will be requested to complete a Lateral Flow test (LFT) prior to each testing day to further protect researchers and other participants from COVID-19. You are asked to follow government and university guidelines with regard to reducing the risk of Covid-19 at testing days, and if you need any further information on the university guidance and risk assessment, please contact the lead researcher.

How will confidentiality be assured?

Your data will be anonymised using codes, and prior to data analysis all data will be held securely on a password protected computer/laptop and will not be shared outside of the research team. No personal data will be shared, and you will not be identified in any resultant outputs such as the student thesis or publications. Please see the Privacy Notice for further details.

What will happen to the results of the research?

The results of the research will be presented in a PhD thesis submitted to the Department of Sport and Exercise Sciences at Durham University, conference talks and published research papers. No names or other identifiable features will be used in any output.

If you have any questions related to the project, please contact the lead researchers:

Thomas Goodbourn
Email: thomas.a.goodbourn@durham.ac.uk
Supervisor name: Dr Karen Hind
Address: 42 Old Elvet, Durham, DH1 3HN
Email address: karen.hind@durham.ac.uk

If you are happy with the answers to your questions, please complete and sign the enclosed Informed Consent Form.

APPENDIX I: RISK ASSESSMENT - PILOT STUDY

Name of researcher(s):	Thomas Goodbourn
Email Address(es) of researcher(s):	thomas.a.goodbourn@durham.ac.uk
Project Title:	*In-vivo validation of head impact telemetry for the measurement of linear and angular acceleration in rugby union*
Project Funder (where appropriate):	-
When do you intend to start data collection?	30/04/2021
When will the project finish?	31/12/2021
Student ID: Degree, year and module: Supervisor:	**OMITTED** 2nd Year PGR (PhD) Student Dr Karen Hind & Mr Jonathan Frawley

A) POTENTIAL RISKS TO PARTICIPANTS

What risks to participants may arise from participating in your research?	How likely is it that these risks will actually happen?	How much harm would be caused if this risk did occur?	What measures are you putting in place to ensure this does not happen (or that if it does, the impact on participants is reduced)?
Irritation from sensor adhesive Psychology of being test – concern over why they are being tested Media Interest Minor injuries from rugby drills	Low Low Low Low Low/Medium	Low-Medium Medium-High Medium Low/Medium Significant	Medical team will identify any player allergies Education on what the testing involves through presentations and provision of info sheets to ensure players fully understand the person of the research Due to the highly topical nature of the research, the study may generate media attention. Participants will be informed of this prior to involving themselves in the study. Researchers have discussed drills included in the study with rugby

Exposure to COVID-19			experts. All drills and plans for the study will be agreed on with expert prior to the recording days. None of the drills included in the study will be outside of the participants usual rugby activities. See COVID-19 Risk Assessment.

B) POTENTIAL RISKS TO RESEARCHERS

Research Site Location/Address: Durham University

What hazards or risks to you as a researcher may arise from conducting this research?	How likely is it that these risks will actually happen?	How much harm would be caused if this risk did happen?	What measu this does no impact on re
Exposure to COVID-19	Low/Medium	Significant	See COVID

Durham University

Inspiring the extraordinary

COVID-19 Risk Assessment - Pilot Study

Completed by: Mr Thomas Goodbourn
Date completed: 12/04/21

Action to be considered	**Action taken (to be completed by researcher in association with participant gatekeeper)**	**Significance of risk (low, medium, high)**
General guidance		
Ensure researchers have read and understood the RFU guidance on mitigating the risks of COVID-19	All researchers have already read the documents.	LOW
Ensure details of researchers have been shared with DSES COVID-19 officer	Details of all researchers that will come into contact with participants will be provided to the DSES COVID officer (Mr Rob Cramb).	LOW
Ensure compliance with Test and Trace by keeping a register (including contact details) of those researchers present at recording sessions. These registers should be held in line with the university's data storage policy.	A data log to track exposure between researchers and participants including times and places will be created and regularly updated. This data log can be provided to the COVID officer upon request.	MEDIUM
Ensure all participants have signed the participant consent form prior to testing	The deadline for signing of participation consent form will be two days prior to first sampling day.	LOW
Ensure all participants are aware of all COVID-19 policies and processes in advance of testing	Regular updates will be provided to participants on which days will be test days. Participants are expected to adhere to all university and RFU guidelines regarding COVID-19 where applicable.	MEDIUM
Ensuring appropriate provisions in place to maintain social distancing guidance and that participants are made aware of the policy in place around usage. This should include: timings, how participants enter and exit the pitch, any process/cleaning before etc.	Separate provisions in place for each section. The university has already made provisions to ensure minimum possible exposure to COVID-19. In Maiden Castle, one-way systems are in place, face-coverings are mandatory and social distancing guidelines are in place at all times for	HIGH

	participants, researchers and staff. Measuring temperature and hand sanitizing on entry to Maiden Castle are mandatory. Timings: The researcher will provide details, as to when and where testing will take place. Participants will be informed of this one week prior to the recording day. Processes/Cleaning: All researchers will sanitize on arrival and will wash hands/re-sanitize at regular intervals. All Protxx sensors will be sanitized before and after use to prevent cross contamination. Sensors will only be used a maximum of twice per week, with a minimum of 72 hours between test days. Sensor application will be completed by the lead researcher to limit participant exposure to external individuals. When appropriate, the researchers will limit their proximity to participants and adhere to appropriate social distancing procedures.	
Handwashing facilities (including soap and water) are available. Alternatively (or additionally) provide sufficient hand sanitiser. Regular hand washing should be encouraged.	The university has provided hand sanitizer and hand washing facilities around the campus and these should be used at regular intervals. The researchers will also provide their own hand sanitizer and wear appropriate PPE to reduce the risk to participants and themselves.	LOW
Ensure that disposable tissues/paper towels/anti-bacterial wipes are available to reduce the threat of	Disinfectant wipes will be provided by the researchers for the cleaning of sensors.	LOW

transmission. Consider how these are disposed of following use e.g. sealed bins	Also, disposable gloves, face coverings (FFP3) and face shields will be worn when in close proximity to participants.	
Display of education pieces, such as a symptoms chart and handwashing guidance, to raise awareness and promote safe practices	The university already provides relevant handwashing and other guidance posters around the stadium, clearly showing the correct procedures and relevant government advice.	LOW
Consider how to manage non-compliance with actions taken to manage the risks of COVID-19	The university already has set out a disciplinary process to deal with non-compliance to the new COVID rules. Initial stages should focus on warnings and education around the procedures. Repeat offences must be dealt with seriously to keep other participants, staff and researchers safe and to discourage further transgressions.	LOW
Provisions in place to manage arrival/departure of individuals to/from the stadium	One-way system will be in place around Maiden Castle. The researchers will stagger the arrival of different groups of participants to reduce the number of people of site at any one time.	LOW
Testing Guidance		
Ensure Protxx sensors are cleaned and disinfected before and after use.	All Protxx sensors will be sanitized before and after use to prevent cross contamination. Sensors will only be used a maximum of twice per week, with a minimum of 72 hours between test days. Sensor application will be completed by the lead researcher to limit participant exposure to external individuals.	MEDIUM
Ensure, where possible, limitation of sharing of equipment e.g. GPS devices, heart rate monitors	All participants will be assigned a personal GPS device, GPS vest holder, heart rate monitor and strap	MEDIUM

	which will remain the same for the duration of the recording session to reduce risk of COVID-19 exposure. All devices will be sanitized before and after use.		
No close physical contact (including hand shaking, huddles, sharing of water bottles etc.) in line with government guidance. This extends to pre, during and post-session meetings, briefings, de-briefs, and any breaks in play.	All participants have been informed by the researchers that unless participating in a drill, they will be required to socially distance as advised by the government guidelines.	LOW	
Ensure appropriate First Aid provisions are accessible (**https://www.sja.org.uk/get-advice/first-aid-advice/covid-19-advice-for-first-aiders/)**	All first aid kits by the pitches will have a box of gloves and masks with them. First aid provision is covered by onsite first aiders at Maiden Castle.	LOW	
Consider whether personal protective equipment (PPE) is required to safely conduct testing (Researchers, assistants, etc.)	Researchers will all wear PPE (face coverings, face shields and disposable gloves) when at the stadium.	LOW	
Ensure social distancing is maintained for participants and researchers during breaks in session.	All participants, staff and researchers will abide by social distancing rules as outlined by RFU, Durham University, and national government guidelines.	LOW	

Appendix J - Department for Culture, Media and Sport (DCMS) Submission (2021)

https://committees.parliament.uk/writtenevidence/25335/html/

Head Impacts in English Premiership Rugby Union

The research is a multi-modal evaluation of head impacts in professional rugby union players (head impacts, video analysis, blood markers, King Devick screening). We are measuring head impacts using Protxx sensors which are worn behind the ear. The study includes one professional rugby union club, with data collected from home matches and contact training sessions during the 2019-2020 Championship season, and the 2020-21 Premiership season. The research has received no external funding and involves a self-funded, full-time PhD student.

Sample findings

This data has been taken from a sample of two Premiership/European rugby union matches and two contact training days (two sessions on each day) during the current (2020-2021) season. The summary includes 47 players, although some players feature multiple times within the selected sample recording sessions. Players were divided into the following groups:

Table 1. *Player position groups*

Player Group	Player Positions
Group 1	Tighthead Prop, Hooker & Loosehead Prop
Group 2	Second Row
Group 3	Blindside Flanker, Openside Flanker & Number 8
Group 4	Scrum Half & Fly Half

Group 5	Inside Centre & Outside Centre
Group 6	Wing & Fullback

'TG25 usually plays in the second row, therefore, in training sessions he will always be listed in PG2, however, on occasion, TG25 plays in the back row for some matches and so will be listed as PG3 when that occurs.'

In the event of an individual playing different positions across multiple groups, if it was during a match, they were assigned to the group for the position that they were playing. However, during a training session the player would be assigned to the group for the position that they played most often. For example:

Although there is not a numerically equal representation of all player groups in this snapshot, the data is representative of the traditional distribution of players across player groups, usually seen in a matchday squad.

Impact data is separated into two main metrics: linear force (g) and angular force (rads/s^2). In line with previous research (King et al., 2015), the minimum thresholds of 10g and 4600 rads/s^2 have been applied to filter out impacts considered to be negligible in causing subconcussive or concussive impact. Over 7,500 impacts registered over these thresholds in the two matches and a further 4,000 over threshold impacts were recorded on the two training days.

General Summary

Table 2. *Mean impact frequency per player*

Recording Session Type	Individual mean impact frequency (±SD)
MATCH	186 (74)
TRAINING	107 (55)

Impact Thresholds

We applied impact thresholds to categorise the impact forces. These thresholds were calculated from the 50th (small), 75th (medium) and 90th (large) percentiles of the match data sample and are an indication of what trends further data analysis might indicate. Threshold brackets needed to be exclusive to avoid repetitions of a singular impact therefore:

Table 3. *Cumulative impact force distribution*

	Impact Force Distribution (Team)					
	Cumulative Frequency (Linear)			Cumulative Frequency (Angular)		
Recording Session Type	LARGE	MEDIUM	SMALL	LARGE	MEDIUM	SMALL
MATCH	409	613	613	345	516	516
TRAINING	122	284	448	101	181	335
	Total match impacts = 4087* Total training impacts = 2285*			Total match impacts = 3443* Total training impacts =1684*		

*impacts <10 g and less than <4600 rads/s^2 classified as negligible

Impacts by Playing Position

Number of Impacts

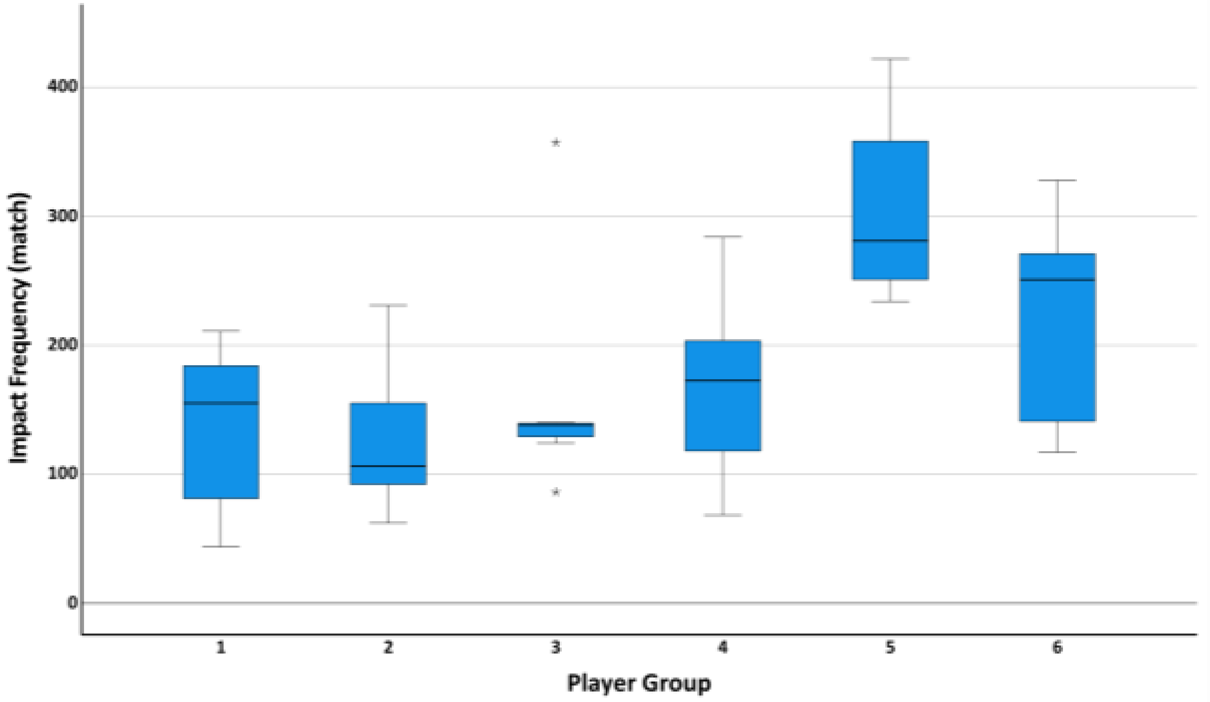


Figure 1. *Impact frequency by player group (match)*

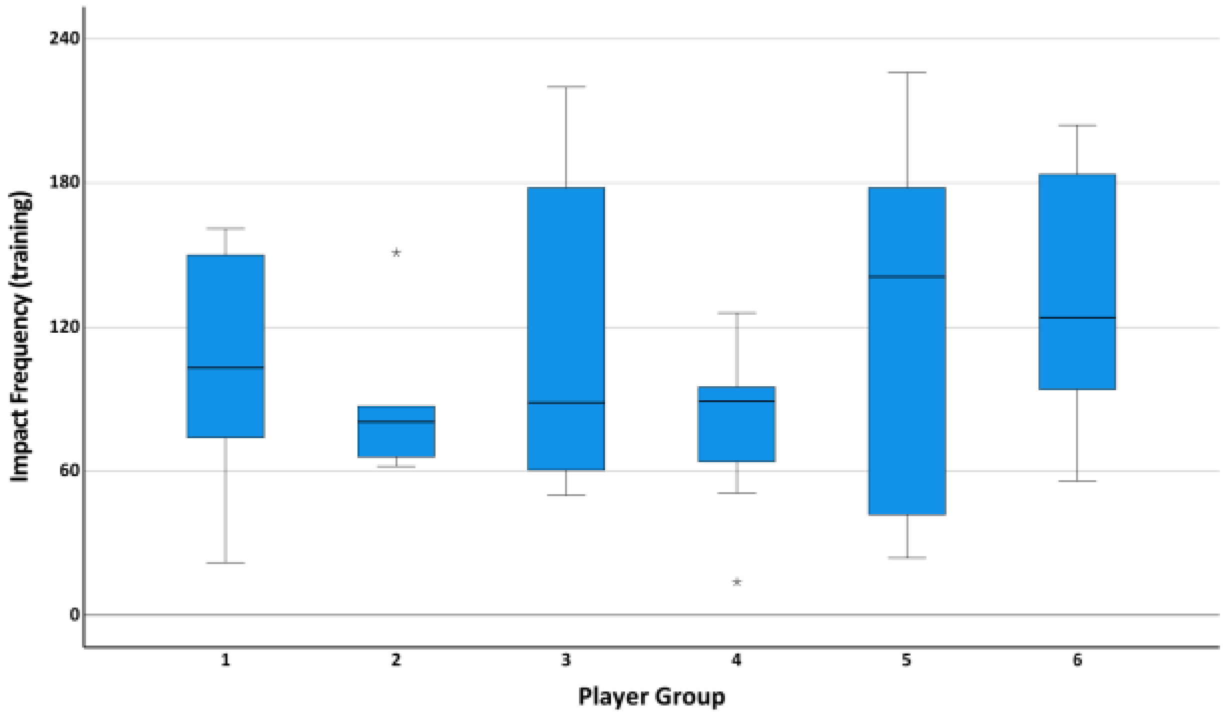


Figure 2. *Impact frequency by player group (training)*

Figure 1 and Figure 2 indicate the distribution of impacts (combined linear and angular) across the six player groups in matches and training.

Magnitude of Impacts

Table. 4. *Distribution frequency of mean impact force per player by player group (match)*

	Mean Linear Impact Distribution (±SD)			Mean Angular Impact Distribution (±SD)		
Player Group	LARGE	MEDIUM	SMALL	LARGE	MEDIUM	SMALL
1	4 (3)	12 (6)	17 (6)	5 (3)	10 (4)	15 (9)
2	6 (3)	13 (4)	13 (6)	5 (3)	10 (6)	16 (4)
3	8 (4)	17 (3)	12 (6)	6 (3)	10 (4)	17 (11)
4	2 (2)	10 (6)	18 (9)	5 (4)	8 (6)	12 (9)
5	30 (9)	22 (7)	25 (8)	24 (23)	20 (12)	15 (6)
6	4 (1)	15 (8)	21 (15)	4 (1)	8 (3)	10 (2)

Table. 5. *Distribution frequency of mean impact force per player by player group (training)*

	Mean Linear Impact Distribution (±SD)			Mean Angular Impact Distribution (±SD)		
Player Group	LARGE	MEDIUM	SMALL	LARGE	MEDIUM	SMALL
1	3 (2)	5 (3)	12 (7)	2 (1)	5 (4)	8 (4)
2	4 (2)	8 (4)	7 (5)	3 (3)	6 (1)	8 (2)
3	4 (3)	6 (4)	8 (4)	3 (3)	5 (3)	7 (3)
4	< 1 (0.8)	5 (3)	6 (3)	1 (1)	2 (2)	7 (3)
5	2 (1)	9 (6)	16 (16)	2 (1)	4 (2)	8 (4)
6	2 (3)	6 (2)	15 (14)	2 (2)	2 (2)	9 (5)

Example interpretation of Table 4 and Table 5:

'The average individual in player group 1 received 4(±3) large linear impacts, 12(±6) medium linear impacts and 17(±6) small linear impacts per match (Table. 4.). In addition, the average player group 1 individual also received 5(±3) large angular impacts, 10(±4) medium angular impacts and 15(±9) small angular impacts per match (Table. 5.)'

Linear and angular impacts do not usually occur in isolation and so, a single impact event could result in sensors recording a linear and angular value.

Linear Impacts

Inter-group:

- Player group 6 received significantly more *large* linear impacts than player group 4 during matches.
- Player group 5 receive significantly more *large* linear impacts than all the other player groups during matches.

Intra-group:

Player group 3 received significantly more *medium* linear impacts in matches than in training.

Player group 5 received significantly more *large* and *medium* linear impacts in matches than in training.

Angular Impacts

Intra-group:

Player group 5 received significantly more *medium* angular impacts in matches than in training.

Player group 6 received significantly more *medium* angular impacts in matches than in training.

Considerations

This data is only a sample from the full study, representing two matches and two training days. Therefore, it may not be truly representative of the final outcomes of the main research study. At the writing of this report, head impact data has been collected at 19 matches and 13 training days (26 sessions). The data will be written for peer reviewed publication over the next 12 months.

The sensors are not able to record maximum linear impact forces that are >27g, although there is no cap on maximum measurement of angular impact forces. Positional corrections of the sensor to account for centre of gravity (COG) were not applied to the sample data.

The thresholds for *large*, *medium*, and *small* linear and angular impacts are generated from statistical indications rather than as a result of proven neurophysiological injury indications. The main study includes analysis of blood biomarkers of neurological trauma, and the outcomes of this analysis will potentially provide greater insight into more appropriate thresholds based upon biomarkers.

Researchers: Dr Karen Hind, Mr Thomas Goodbourn and Mr Jonathan Frawley.

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