Sport-Related Concussion and Video Analysis of Wearable Impact Sensor Data in Rugby League

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A thesis submitted in fulfilment of the requirements for the degree of
Master of Philosophy

November 2021

Statement of Originality

I hereby certify that the work embodied in the thesis is my own work, conducted under normal supervision. The thesis contains no material which has been accepted, or is being examined, for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made. I give consent to the final version of my thesis being made available worldwide when deposited in the University's Digital Repository, subject to the provisions of the Copyright Act 1968 and any approved embargo.

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Acknowledgement of Authorship

I hereby certify that this thesis is in the form of a series of papers. I have included as part of the thesis a written declaration from each co-author, endorsed in writing by the Faculty Assistant Dean (Research Training), attesting to my contribution to any jointly authored papers.

Publication 1: Carey, L., Stanwell, P., Terry, D.P. *et al.* Verifying Head Impacts Recorded by a Wearable Sensor using Video Footage in Rugby League: a Preliminary Study. *Sports Med - Open* **5,** 9 (2019)

By signing below I confirm that Lauchlan Carey contributed to study design, data collection, and the drafting, revising and finalising of the manuscript to the publication entitled "Verifying Head Impacts Recorded by a Wearable Sensor using Video Footage in Rugby League: a Preliminary Study."

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Publication 2: Carey, L., Terry, D.P., McIntosh, A.S. *et al.* Video Analysis and Verification of Direct Head Impacts Recorded by Wearable Sensors in Junior Rugby League Players. *Sports Med - Open* **7,** 66 (2021)

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Acknowledgements

Firstly I would like to acknowledge and thank Associate Professor Andrew Gardner and Associate Professor Peter Stanwell who both contributed an enormous amount to this thesis. The continued support, advice and expertise they provided has help shaped this body of work and their input has been greatly appreciated. They were both available and happy to help whenever necessary and took the time to guide me through the whole process. Another big thankyou to the 2016 Central Charlestown Butcher Boys Rugby League Club and 2017 Newcastle Knights Harold Matthews squad for agreeing to partake in our research studies. Thank you to my third supervisor Dr Sharmaine McKiernan for providing guidance and getting me heading in the right direction from the outset. To everyone who contributed to the publications in this thesis I thank you for your time and expertise in helping shape my first two research papers.

Lastly I'd like to thank my family and partner Christine who were supportive and understanding throughout the whole journey. Without their love and support this thesis would not have been possible and I am forever grateful.

Note

The referencing style in this thesis changes for the two publications due to journal specific requirements

Abstract

Background: Rugby league is a full-contact collision sport that carries a high risk of sport-related concussion. There are few studies in rugby league that utilise video analysis and wearable head impact sensor data together to investigate head impact exposures across a full season.

Purpose: To verify wearable head impact sensor data using video analysis and describe game-play characteristics and head biomechanics that contribute to concussion in rugby league.

Methods: The x-Patch^{TM} was used for a season of men's semi-professional and junior boys representative level rugby league. A total of twenty-nine players were monitored and game-day footage by a trained videographer was recorded and analysed to verify head impacts and describe impact rates, playing and gameplay characteristics of video-verified head impacts.

Results: The x-Patch^{TM} recorded a total of 1,403 impacts ≥20g between game start and finish across the two studies in this thesis, of which 1,296 (92%) were verified on video. In study ,1 the number of video-verified impacts ≥20g, per playing hour, was 7.8 for forwards and 4.8 for backs. Impacts resulting in concussion had a much greater peak linear acceleration (M = 76.1g, SD = 17.0) than impacts that did not result in concussion (M = 34.2g, SD = 18.0; Cohen's d = 2.4). Study 2 found 73.2% of all verified impacts ≥20g where determined to be direct head impacts and occurred at a rate of 5.2 impacts per game hour.

Conclusion: There were high rates of agreement between video-verified and sensor recorded game play impacts ≥20g and also a number of triggered events that occurred during gameplay that did not correlate with an impact on video review. The use of a secondary source, such as video review, to verify x-Patch^{TM} recorded impacts is extremely important when analysing total head impact exposure as failure to remove 'false-positive' impacts may inflate player's cumulative and average head impact exposures.

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Chapter 1 - Introduction

The latest consensus statement from the Concussion in Sport Group (CISG) defines sport-related concussion as “a traumatic brain injury induced by biomechanical forces” (McCrory et al., 2017). Sport-related concussion can be caused by a direct blow to the head, or elsewhere on the body, with an impulsive force subsequently transmitted to the brain causing rapid onset neurological function impairment, which may be prolonged. This typically resolves spontaneously and follows a sequential course however in some cases signs and symptoms can evolve over a number of minutes or hours and can cause long-term neuropathological changes. Both linear and angular acceleration or deceleration forces on the brain cause complex pathophysiological disturbance which induce symptoms such as headaches, dizziness, or loss of consciousness (Meehan & Bachur, 2009). Rugby League is a high-intensity collision sport with a risk of concussive injury for participants. Current literature of concussion in rugby league is small and incidence of concussion varies greatly due to the lack of a consensus ‘definition of injury’ across studies (Gardner, Iverson, et al., 2015a).

The use of sideline analysis and video review has become increasingly common as a method of identifying head impacts and concussions across a large number of professional sports (Davis et al., 2019b). Using video as a secondary source can help improve the identification of game-day concussions for team doctors by providing evidence of injury mechanism or clinical signs (Davis & Makdissi, 2016). Many professional sporting bodies have introduced real-time sideline video to assist with recognising possible concussive injuries and to reduce the number of missed concussions. The ability to review an incident repeatedly from multiple camera angles, and at multiple speeds, can help assess the mechanism of injury and the presence of video identifiable signs of concussion (Davis et al., 2019b). Due to the high speed of gameplay in rugby league, in-game identification and management of concussion is challenging. Sideline video review is increasingly being used to improve the decision-making process for club medical staff. Good knowledge and experience with rugby league is essential for any sideline video reviewers, as the complexity of rugby league collisions (i.e. potentially more than one significant impact in a tackle event) means there are a number of variables in identifying suspected concussions in game-play incidents (Gardner, Levi, & Iverson, 2017).

Microtechnology and impact sensors, that include accelerometers and gyroscopes, may help us better understand sport-related concussions through the assessment of head biomechanics (Brennan et al., 2016). A range of helmeted and non-helmeted devices have been used to collect *in vivo* data in a range of sports (O'Connor, Rowson, Duma, & Broglio, 2017). Current non-helmeted wearable impact sensors, suitable for use in rugby league, contain a triaxial accelerometer and gyroscope to measure linear and angular accelerations and decelerations and estimate forces applied to the head during collisions. This study will utilise the X2 x-Patch™ (X2 Biosystems; Seattle, WA) sensor worn behind the ear of each participating player. The current literature which looks at head impact exposure in rugby league is scarce. Only two studies have utilised the x-Patch™, without video review as a secondary source, to investigate the distribution of head impacts across a season of junior (King, Hume, Gissane, & Clark, 2017) and women's rugby league (King, Hume, Gissane, Kieser, & Clark, 2018). The purpose of this study is to utilise X2 x-Patch™ sensor technology with video review to verify sensor accuracy and head biomechanics that contribute to concussion in rugby league at a semi-professional and junior representative level.

1.1 Literature Review – Rugby League and Sport-Related Concussion

1.1.1 Rugby League and Incidence of Concussion

A popular team sport played all over the world, rugby league is a high-intensity physical collision sport that carries the risk of injury at all competitive levels of play (Hoskins, Pollard, Hough, & Tully, 2006). Each team consists of thirteen players plus four interchange players, which can be rotated on and off the field at any point. Elite levels of the sport utilise restrictions on the number for interchanges a team is allowed to make. Teams ordinarily consist of six forwards (two props, one hooker, two second rowers and one lock) who are generally stronger and involved in more high impact collisions and seven backs (one half-back, one five-eighth, two wingers, two centres and one fullback) who are usually faster, more agile, but also involved in tackles and collisions (King, Hume, Milburn, & Guttenbeil, 2010). Interchange players usually consist of more forwards than backs and can include utility players that can play both forward and back. Played on a rectangular field, 100m in length, the game is comprised of two continuous 40-minute halves, where the main objective is to score a try by placing the ball on the ground over the goal line. Teams get a set of six tackles to score before an immediate handover of possession to the opposition meaning players are constantly changing between attacking and defending (Gardner, Iverson, et al., 2015b). The ball must be thrown backwards or kicked forward and the main method of progressing the ball forward is running at speed towards the defensive line. The objective of the defending team is to tackle the attacker who has possession of the ball with any number of tacklers allowed (Hoskins et al., 2006). The game is played at a high pace and to be successful players must possess an elite combination of speed, stamina, strength and agility which in turn leads to a number of high speed, high impact collisions (Gibbs, 1993).

Australian professional rugby league clubs have been subject to a variety of studies into the incidence and mechanism of concussion over a number of years (Gardner, Iverson, et al., 2015a). Gibbs first reported the incidence of injuries in professional rugby league across 3 seasons from 1989-91, with the definition of an injury requiring the player to miss the subsequent week (Gibbs, 1993). It was found that only 5 of 141 (3.5%) total injuries were as a result of concussion, less common than other types of injuries such as muscle strains, contusions, joint injuries, abrasions and lacerations. Interestingly, there were a further 23 incidents noted, but not included, where a player was treated on the field for mild concussive symptoms, but not removed and did not miss any games. During a prospective study from the 1992 professional season, concussion accounted for 8.5% of total injuries in rugby league, much higher than Australian Rules Football (3.6%) and rugby Union (5.3%) (Seward, Orchard, Hazard, & Collinson, 1993). In this study the definition of injury only needed the player to receive specific medical attention and did not require the player to miss the subsequent game. Changing definitions and rule changes introduced to help prevent concussive injury led to greatly varying reported incidence rates (Gardner, Iverson, et al., 2015a). A 15 year study conducted at one professional club from 1998 until 2012 reported the incidence of concussion to be 28.3 per 1,000 player match hours (Savage, Hooke, Orchard, & Parkinson, 2013). The incidence of medically diagnosed concussions in three clubs in the National rugby League was 14.8 and 8.9 per 1000 player match hours in 2013 (Gardner, Iverson, Quinn, et al., 2015) and 2014 (Gardner, Howell, Levi, & Iverson, 2017) respectively.

In 2014 the Australian elite level rugby league competition, the National Rugby League (NRL), introduced a new ‘Head Injury Assessment’ (HIA) policy following a review of their policies as the public awareness and ongoing player safety concerns surrounding concussion grew. This involved mandatory removal of players showing any observed, self-reported or teammate/trainer reported signs of concussion. A 15-minute window was given for the athlete to be assessed by the clubs' medical officer. If cleared of any concussion symptoms, they were returned to the play without the team losing any of their eight allotted limited interchanges for the match (Gardner et al., 2016). However, if the player was evaluated but not diagnosed with a concussion, the team was forced to use one of their interchanges. During its first season, the HIA was used 167 times with an incidence rate of 24.0 per 1,000 NRL player match hours, or approximately one every 2.41 games (Gardner et al., 2016). The incidence rate for medically diagnosed concussion during the same season was much lower at 8.92 per 1,000 NRL player match hours, or approximately one concussion every 3.35 games, suggesting the policy was being used as intended (Gardner, Howell, et al., 2017). Playing position may also influence the risk of concussive injury with forwards at greater risk of injury than backs (Gabbett, 2005; Gissane, Jennings, Cumine, Stephenson, & White, 1997). In the 2014 NRL season, forwards (56%; 93/167) accounted for more uses of the HIA than backs (24%; 40/167) and interchange players (20%; 34/167) (Gardner et al., 2016). The "hit-up" (the action of a player carrying the ball, usually at speed, towards the defensive line resulting in a collision or tackle) accounted for a large percentage of uses of the HIA at 62% with no other play accounting for more than 5%. King and colleagues reported that the ball carrier accounted for 53% of all tackle-related injuries and the tackler 47% (King, Hume, & Clark, 2012). Concussive injuries as per the use of the HIA resulted in a higher percentage of injury to the tackler (55%) compared to the ball carrier (43%) suggesting that the ball carrier is at greater risk of injury as a whole but the tackler is more susceptible to concussive injury (Gardner et al., 2016).

1.1.2 History and Recognition of Sport-Related Concussion

Over time our knowledge, awareness and surveillance of sport-related concussion, along with changes in working definition and a lower diagnostic threshold, has seen a steady increase in the incidence of reported concussion across a wide range of sports (Lincoln et al., 2011). The first reports of potential later life neurological health problems from sport-related concussion came in the 1920's with Dr Harrison Martland describing a medical pathology with parkinsonian-like features caused by repeated blows to the head or jaw, particularly in boxers, he labelled "punch drunk" (Martland, 1928). In his study, Martland described the classic clinical presentation of punch drunk boxers and noted that symptoms could present immediately after injury. His work laid the foundation for concussion research and his warnings on repetitive head trauma risks in sports still hold up to this day (Changa, Vietrogoski, & Carmel, 2017). Parker built on Martland's theory several years later, providing further evidence that punch drunkenness can present as a 'medley' of symptoms over varying time periods in professional boxers, and calling the condition traumatic encephalopathy (Parker, 1934). Millspaugh followed, and in 1937 introduced the term 'dementia pugilistica' as a variation of punch drunk syndrome, specifically relating this to professional boxers (Millspaugh, 1937). In his findings he analysed the regulations, rules and precautions taken by the boxing committee and proposed that medical personnel must be responsible enough to stop the fight when necessary. Critchley, in a 1949 study of 21 punch drunk patients, stated that the interval between taking up boxing and the development of neurological signs or symptoms averaged at 16 years but ranged anywhere from 6 to 40 years (Critchley, 1949). Here Critchley referred to the term as chronic traumatic encephalopathy which in a later study he changed to progressive traumatic encephalopathy (Critchley, 1957).

Chronic Traumatic Encephalopathy (CTE) was the subject of numerous studies on the brains of boxers, military personnel and civilians and in a later review of published cases, McCrory noted that cognitive impairment was typically seen in boxers 10-20 years post retirement (McCrory, 2011). Corsellis and colleagues published the first robust neuropathological study looking at patient histories and autopsy findings from 15 retired boxers whose brains were held in a "brain bank' (Corsellis, Bruton, & Freeman-Browne, 1973). They reported that cerebral degeneration was the most likely cause of a multitude of symptoms displayed by their patients, from parkinsonism to changes in cognition. Omalu and colleagues were the first to report cases of CTE in American Football with autopsy findings in a retired professional player (Omalu et al., 2006; Omalu et al., 2005). These cases were the start of a large number of studies comparing autopsy findings with symptoms present during an athlete's post-sporting life (McKee et al., 2009) and paved the way for the 'modern' version of CTE (Gardner, Iverson, & McCrory, 2014). To date CTE still cannot be diagnosed *in vivo* and it is becoming increasingly important to recognise even the mildest concussive injury.

Currently there is no method to accurately predict long-term neurological impairment from a concussive impact and limited to no evidence to support the notion that these injuries '*cause*' CTE (Saigal & Berger, 2014). Some researchers have suggested that long-term adverse effects may be attributed to cumulative exposure to sub-concussive events with an absence of neurological signs and symptoms that lead to a clinical diagnosis of concussion (Bailes, Petraglia, Omalu, Nauman, & Talavage, 2013). Bailes and colleagues defined sub-concussion as 'a cranial impact that does not result in known or diagnosed concussion on clinical grounds' and emphasised the need for further research to help create a clear definition of the phenomenon known as 'sub-concussion' (Bailes et al., 2013; Mainwaring, Ferdinand Pennock, Mylabathula, & Alavie, 2018). A comprehensive review by Mainwaring and colleagues determined there was an ambiguous and misleading use of the term ‘sub-concussion’ across studies and recommended refraining from using this term due to the lack of precision in its definition (Mainwaring et al., 2018). Instead the term ‘head impact’ is more accurate and future research should look to focus on the cumulative effects of mild, repetitive head impact exposure. The use of impact sensors in this study will help to quantify the head impact exposure received by rugby league players and quantify these so-called ‘subclinical injuries’ that could potentially lead to long-term microstructural and functional neurological changes. Research into these subclinical impacts is becoming increasingly important, however there is still more investigation needed into consequences and diagnosis of larger single impact concussive impacts (Mainwaring et al., 2018).

Symptoms of concussion can be difficult to detect during gameplay or training making it one of the most challenging injuries in sport to diagnose. Approximately 90% of sport-related concussions occur without loss of consciousness (Gardner, Iverson, et al., 2015b) and the majority show no obvious signs of neurological deficit. Effects of concussion are commonly seen acutely, either instantaneously or within minutes to hours of impact. Late-onset signs and symptoms have also been recognised and can occur days or weeks following impact (Edwards & Bodle, 2014). Symptoms can be divided into four main categories: somatic (physical), cognitive, emotional and sleep/wake disturbance (Table 1) (Weinberger & Briskin, 2013). Somatic signs are the most easily recognisable with headaches, often triggered or exacerbated by loud noises and bright lights, being the most commonly reported symptom of concussion and dizziness or balance problems the second most common (Upshaw, Gosserand, Williams, & Edwards, 2012). The presence of a symptom is an indication but does not confirm a diagnosis of concussion as several symptoms are non-specific to concussion (McCrory et al., 2017). Resolution of signs and symptoms occurs spontaneously and rapidly in most cases however, some people suffer long term lingering effects (Laker, 2015).

Table 1. Signs and symptoms of concussion

Somatic	**Cognitive**	**Emotional**	**Sleep/wake disturbance**
Headache	Feeling mentally "foggy"	Irritable	Drowsiness
Dizziness/Balance problems	Feeling slowed down	Sadness	Sleep more or less than usual
Nausea/Vomiting	Difficulty concentrating and remembering	More emotional	Difficulty falling asleep
Visual problems	Answering questions slowly	Nervousness	
Fatigue	Repeating questions		
Sensitivity to noise and/or light	Confused about recent events, information or conversations		
Dazed or stunned			
Numbness or tingling			

(Harmon et al., 2013)

Concussion is induced by mechanical forces and unlike most injuries does not typically result in structural damage, but rather abnormal function at the cellular level (Steenerson & Starling, 2017). Both linear and angular forces cause acceleration and deceleration of the brain within the skull and in turn, damage to its microstructure (Giza & Hovda, 2001). Subsequent biomechanical alterations cause abnormal cellular functions leading to neurotransmission and neurometabolism impairment (Steenerson & Starling, 2017). Current knowledge of the neurometabolic cascade of concussion can be attributed to previous laboratory research, which has highlighted the damage to the neural cell membrane and the flow on effect of abnormal neural events following a concussive impact. "Shearing" and "stretching" forces cause a temporary disruption to the membrane and an efflux of potassium through voltage-gated channels, termed "mechanoporation", which in turn causes neural depolarisation (Romeu-Mejia, Giza, & Goldman, 2019). This is accompanied by an influx of sodium and calcium which prompts the release of glutamate, an excitatory amino acid, from the neuron causing further depolarisation. To combat this chemical imbalance, sodium-potassium ion pumps increase production, further depleting adenosine triphosphate and glucose reserves. The resultant decrease in cerebral blood flow and increase of calcium in the cell causes lactate build-up, an energy crisis and in turn decrease in mitochondrial function and impaired axonal function (MacFarlane & Glenn, 2015; Narayana et al., 2019). This period of decreased function is usually self-limiting and transient following a single concussive event but can lead to permanent damage. A small amount of people will suffer persistent neurological symptoms beyond the normal recovery period, especially following multiple concussive or even sub-concussive hits. Studies have proven that repetitive injuries and disruption to white matter tracts can lead to permanent degenerative changes (Steenerson & Starling, 2017). It is increasingly possible to observe links between clinical signs and symptoms of concussive injury and pathophysiological changes and understanding these changes remains a key component to prevention of repeated injury (Giza & Hovda, 2014).

Diagnostic neuroimaging has limited value in the acute stages of injury with X-ray, CT, and MRI only able to detect significant structural changes or to exclude the presence of a more serious pathology, such as subdural or intracranial haematoma, and skull or facial fractures. Disturbance to the functional aspects of the brain mean physical structures such as the skull, brain parenchyma and blood vessels appear normal in routine neuroimaging tests including computed tomography (CT) and magnetic resonance imaging (MRI) (Grant, van Rensburg, van Rensburg, & Collins, 2014). Research is still ongoing in a variety of more advanced neuroimaging techniques, including functional MRI, to help better understand the functional deficits or structural pathology that contribute to concussion. Currently cost and availability are limiting the use of many of these technologies and more research needs to be undertaken before they have proven clinical utility.

1.1.3 On-field and Sideline Assessment

On-field assessment of sport-related concussion is a challenging task, usually required to be performed rapidly in a time efficient manner, and by someone with the appropriate medical training. Self-reporting of symptoms is still the easiest and most effective method of immediate post-concussion assessment, but should not be relied on as the sole tool as it can lead to under reporting of signs and symptoms (Broglio & Puetz, 2008). Often athletes will fail to recognise and report symptoms of probable concussive injury, or they may believe the impact sustained was not serious enough to warrant further medical attention. In professional sports, where performance is heavily scrutinised, players desire to stay in the game may lead them to hide symptoms, knowing that self-reporting their symptoms can restrict their playing time and impact on the game (McCrea, Hammeke, Olsen, Leo, & Guskiewicz, 2004; Meier et al., 2015). Not reporting symptoms or the failure to recognise a concussive injury can have potentially catastrophic effects. Receiving another concussion before the symptoms of the first concussion have completely resolved, known as second impact syndrome, has the potential to cause long lasting neurological defects or permanent disability, especially in younger athletes (McLendon, Kralik, Grayson, & Golomb, 2016).

The National Rugby League's HIA policy permits a stoppage in play for the assessment and removal of a player suspected of sustaining a sport-related concussion and further sideline assessment to be conducted. The initial on-field assessment of concussive injuries, usually done ‘on the run’, helps exclude more serious cervical spine and/or brain injury. If there is any concern or uncertainty of concussive injury, the athlete should be removed from play and assessed on the sideline in a quieter, more controlled environment (Putukian et al., 2013). Brief neuropsychological test batteries, focusing on memory and attention, provide the most effective and practical form of sideline assessment (McCrory et al., 2017). In 2004, the Concussion in Sport Group (CISG) created the Sport Concussion Assessment Tool (SCAT) for use by team physicians to assist in the evaluation of sport-related concussions (McCrory et al., 2005). This standardised assessment tool combined a number of separate tests designed for assessing symptoms, cognitive status and neurological functioning leading to a diagnosis of sport-related concussion. The SCAT has been revised multiple times with the most current version, the SCAT5, reviewed at the Fifth International Consensus Conference on Concussion in Sport in Berlin in 2016 (McCrory et al., 2017).

Currently the most effective and well-established method of sideline evaluation, the SCAT5 is designed for use by physicians and licensed healthcare officials only. It is essential that the athlete is removed from play and assessed in a quiet, controlled environment as the SCAT5 can take over 10 minutes to properly administer (Echemendia et al., 2017b). The SCAT5 consists of six sections:

1. *Immediate or on-field assessment* – observable signs of concussive injury including immediate red flags, cervical spine assessment, Glasgow Coma Scale (Jennett & Bond, 1975) and Maddocks memory assessment questions (Maddocks, Dicker, & Saling, 1995)
2. *Symptom evaluation* – 22 signs and symptoms of concussion rated by the athlete from 0-6 for a total severity score out of 132
3. *Cognitive Screening* – orientation tasks, immediate memory and concentration tasks reciting word, digit and months lists back to the physician

4. *Neurological Screen* – simple eye tracking, reading, movement and gait tasks and balance examination using the modified balance error scoring system (Guskiewicz, 2003)
5. *Delayed Recall* – Reciting of previous words used in cognitive screening section no sooner than 5 minutes after the initial immediate recall
6. *Decision* – addition of all sections and final verdict signed off by trained physician or licensed healthcare professional

The SCAT5 is useful for evaluation of concussion immediately after injury in individuals 13 years or older (Echemendia et al., 2017b). For paediatric athletes aged between 5 and 12 years old the Child SCAT5 provides a tool consistent with the SCAT5 with changes to some components more appropriate to children (Davis et al., 2017). A separate Concussion Recognition Tool 5 (CRT5) was developed at the same meeting to assist non-medically trained people to identify and appropriately manage (i.e., remove the athlete immediately from play) suspected concussions (Echemendia et al., 2017a). This “recognition and removal” tool is important as the presence of a trained medical professional is not possible for many amateur sporting competitions. It is not intended as a tool for diagnosis of concussion, but rather the recognition of symptoms and potential concussions so the athlete can be removed from play and transferred to an appropriate medical professional.

Further education for players, coaches, and parents can help implement effective concussion policies and action plans to prevent more serious outcomes for affected athletes (Guskiewicz & Broglio, 2011). Sideline testing using the SCAT5, whilst quick and efficient, is designed for rapid screening rather than a definitive diagnosis of sport-related concussion and should not replace comprehensive neurological evaluation which remains the standard for concussion diagnosis (Schepart & Putukian, 2018). The SCAT5 should not be used as the sole tool to exclude or diagnose concussion and athletes may still show signs and symptoms for several days post injury making ongoing assessment essential.

1.1.4 Management and return to play

Any athlete suspected of sustaining a sport-related concussion, regardless of sex, age, and level of participation, should be removed from play immediately and not return until they are declared symptom free by a medical professional. The team's physicians should determine if the athlete requires further evaluation in an emergency room, doctors' office or sports concussion clinic if available. In the case where no physician is available, the athlete should be referred directly to either of these medical treatment options before being allowed to return to play. A detailed medical history and further neurological examinations completed in a calm surrounding by trained medical professionals is essential for management and if required, further intervention at an appropriate treatment centre (Feddermann-Demont, Straumann, & Dvořák, 2014). There is no evidence to suggest pharmaceutical medication can speed up the recovery process however it can be taken temporarily to reduce the severity of some symptoms (d'Hemecourt, 2011). The use of medication, carefully administered and monitored by experienced healthcare providers, should be ceased before return to play as it has the potential to mask symptoms and greatly affect return to play considerations (Doolan, Day, Maerlender, Goforth, & Gunnar Brolinson, 2012).

Due to the variability of signs and symptoms across individual athletes, the management of sport-related concussion can differ. The most recognised method of managing sports related concussion is physical and cognitive rest until the athlete is free of any lingering signs and symptoms (Stillman et al., 2017). Whilst physical rest is easy to understand, cognitive rest is harder to define and monitor as it is difficult to “turn off” brain activity. The evidence that cognitive rest improves outcomes is currently limited and inconclusive however it is shown to be beneficial in easing symptoms in the acute phase of injury (i.e., the first 24-48 hours post concussive impact) (McLeod, Lewis, Whelihan, & Bacon, 2017). Prolonged periods of cognitive and physical rest can have potentially harmful effects and may lead to psychological complications, such as anxiety and depression, and physical deconditioning. Withdrawal from everyday activities such as school, work, involvement in team related activities and electronic devices can impact psychological well-being post injury (DiFazio, Silverberg, Kirkwood, Bernier, & Iverson, 2016). A study of people aged between 11 and 22 presenting to an emergency department displaying symptoms following a concussive injury, found that people resuming non-sport related activity two days post injury showed better outcomes than those with forced five day bed-rest (Thomas, Apps, Hoffmann, McCrea, & Hammeke, 2015). After the initial period of rest, it is recommended to gradually resume physical and cognitive activities, ensuring the level of activity does not exacerbate symptoms. Leddy and colleagues showed that individualised progressive aerobic programs that remain below the symptom exacerbation threshold in both athletes and non-athletes can safely treat post-concussive injury. Through participation in these gradual training programs, patients were able to achieve maximum exertion and readiness to return to play (Leddy et al., 2010).

Neuropsychologists can play an important role in assessment and management of sport-related concussion, with neuropsychological testing an efficient way to assess cognitive function. Whilst considered the gold standard in evaluating sport-related concussion, a full neuropsychological assessment can be a significant and costly undertaking, with brief computerised cognitive evaluation tools a more commonly used method (McCrory et al., 2017). Pre-season neuropsychological testing can be administered and serve as a “baseline” with post-concussion results compared to these pre-season control scores. This should be done after the initial rest period whilst the athlete is asymptomatic and can help to detect subtle changes that may not be obvious to the team physician (Hunt & Asplund, 2010).. Return-to-play is indicated by the athletes return to baseline and completion of a graduated exercise program without exacerbation of symptoms (Darling, Freitas, & Leddy, 2015). Whilst these tests are used regularly, there are question marks over the re-test reliability with little evidence suggesting these scores affect outcomes They should not be used as the sole determinant, but can be used in conjunction with clinical assessments to aid decision-making processes and assist return-to-play decisions.

The graded return-to-activity progression has been widely accepted as the standard of care and management of concussion and should be closely monitored and carefully individualised to the patient to account for modifying factors such as age, sex, previous concussions, and other medical conditions (McLeod et al., 2017). A strategy for gradual increase of activity should be agreed upon by medical personnel prior to the competitive event and should commence immediately after the initial rest period. Both the National Athletic Trainers' Association position statement on management of sport concussion and the Concussion in Sport Groups consensus statement on concussion in sport outline the same six step graduated return-to-play strategy (see Table 2). Typically, there should be a minimum of 24 hours between each level unless there is a return of symptoms in which case the activity step should be immediately stopped and restarted 24 hours later. The entire process should take approximately one week however the physician in control of the assessment can shorten or lengthen the process where appropriate (Broglio et al., 2014; McCrory et al., 2017).

Table 2. Graduated return-to-play strategy

Stage	Activity	Goal of step
1	Symptom-limited/No activity	Daily activities do not provoke symptoms
2	Light aerobic exercise	Walking/cycling at slow-medium pace to increase heart rate
3	Sport-specific exercise	Running drills to add sharper movement
4	Non-contact training	Harder drills to test coordination and increased thinking
5	Full contact training	After medical clearance, normal training activities to restore confidence and assess functional skills
6	Return to sport/play	Normal game play

(Broglio et al., 2014; McCrory et al., 2017)

Due to their developing brains, children and adolescent athletes can have different implications and may require slightly differing sport-related concussion management strategies. Children have a slightly longer risk period for sustaining repeat concussions and increased susceptibility to long-term health problems than people who suffer their first concussive injury in their twenties (Bressan & Babl, 2016). Management strategies should be monitored more closely and potentially lengthened for paediatric patients to ensure they are asymptomatic for a longer period of time before each stage of activity is commenced (McLeod et al., 2017). It is encouraged schools have specific sport-related concussion policies to aid with paediatric students' recovery. Whilst everyday cognitive activity, such as schoolwork, is not dangerous to the concussed patient, it may exacerbate or prolong symptoms. Depending on the severity of symptoms, additional learning support and flexibility may be needed which could include temporary absence, shortened school day or additional rest periods, quieter environments, reduced workload and time extensions on assignments and homework (Provance, Engelman, Terhune, & Coel, 2016; Wing & James, 2013). Returning to school before returning to sport is essential for any paediatric athlete recovering from concussive injury. Similar to the graduated return-to-play strategy, McCrory and colleagues created a four-step graduated return-to-school strategy to aid with the recovery process for child and adolescent athletes (see Table 3).

Table 3. Graduated return-to-school strategy

Stage	**Activity**	**Goal of step**
1	Everyday home-based activities (e.g., reading, screen time)	Gradually return to daily activities whilst remaining symptom free
2	School based activities (e.g., homework, reading)	Increasing child's tolerance to cognitive work or activities
3	Part-time return to school (e.g., partial/split school day)	Gradually introducing schoolwork and increasing academic activity
4	Full-time return to school (e.g., completion of full day)	Returning to full academic activities

(McCrory et al., 2017)

1.2 Literature Review - Video review in the identification of concussion

Video review and analysis is becoming an increasingly important tool in recognising sport-related concussion across a large number of professional sporting codes. The first uses of video analysis in concussion were largely for research purposes, to investigate the biomechanics, mechanisms, or game-play situations that contribute to concussive injury (Caswell, Lincoln, Almquist, Dunn, & Hinton, 2012; Koh & Watkinson, 2002; Koh, Watkinson, & Yoon, 2004; Lincoln, Caswell, Almquist, Dunn, & Hinton, 2013). In recent years, a shift of focus has seen the use of video analysis go from a retrospective review tool to a live, sideline surveillance tool to assist medical personnel in identifying potential concussions (Davis et al., 2019b). Video based analysis for the purpose of understanding mechanisms of injury and describing events leading up to high risk situations was first performed in a retrospective study of Norwegian under 21 football matches from 1994-1998 (Andersen, Larsen, Tenga, Engebretsen, & Bahr, 2003). A similar study followed, reviewing the 1999 Icelandic elite football league season to describe playing characteristics and factors leading up to injury situations in the hope of developing injury avoidance strategies (Arnason, Tenga, Engebretsen, & Bahr, 2004). Koh and colleagues were the first to utilise video analysis specifically for concussive injury, analysing situational and contextual factors surrounding direct head impacts in Taekwondo (Koh et al., 2004). This study of a 2001 middle and high school Taekwondo tournament in South Korea, correlated video analysis with direct interviews of participants receiving substantial head blows. The results of the study indicated that there might be significant under-reporting of possible concussions. Further video analysis studies in combat sports have aimed to identify an objective method of determining when to halt professional boxing bouts before they risk becoming fatal (Miele & Bailes, 2007) and determine the incidence and risk factors of knockouts from repetitive strikes in mixed martial arts (Hutchison, Lawrence, Cusimano, & Schweizer, 2014), both with the goal of making their respective sports safer.

The use of video analysis in examining injury mechanisms and game-play characteristics that lead to concussive injury has since spread to a wide range of contact team sports. Injury mechanisms and game situations that led to concussive injuries were analysed across two seasons of high school level lacrosse in boys (Lincoln et al., 2013) and girls (Caswell et al., 2012). The findings from these studies showed the majority of concussive impacts were unintentional, or the affected player was unprepared for contact. Through reporting differences in mechanism of injury across studies, Caswell and colleagues suggested improved player skill might decrease injury risk, with the most common cause in boy's lacrosse being player to player contact and girl's stick to player contact (Caswell et al., 2012). At the professional sports level, a two-part retrospective video analysis of medically diagnosed concussions in the National Hockey League from 2006-2010 aimed to describe players' characteristics and situational factors of concussive injury in ice hockey (Hutchison, Comper, Meeuwisse, & Echemendia, 2013, 2015). Differences in concussion rates between playing positions, locations or "zones" on the ice, time points in the game and points of contact on the body (direct blows to the head by the opposing players shoulder, elbow and gloves) were noted with the hope of future prevention measures and strategies being created to reduce the frequency of concussions. Video analysis of every head injury assessment from a three year period across six professional international and national rugby union competitions described different characteristics and game situations of concussive events, showing that the tackle event exposed the player to the highest risk of head injury, with the tackler sustaining 2.6 head injury assessment's to every 1 of the ball carrier (Tucker et al., 2017).

The first video analysis study in Australian Football aimed to investigate situational factors, mechanism of injury and assess the reliability of video for the assessment of concussion (Makdissi & Davis, 2016b). Many factors assessed on video did not relate to the risk of concussion and showed poor inter-rater reliability. A new standardised tool for concussion surveillance in Australian Football was developed to include factors that may impact risk of concussion, such as site and cause of primary impact, whether a free kick was awarded and injury mechanism. A subsequent study aimed to test the reliability and validity of identifying clinical signs of concussion with video analysis in Australian Football, using eight observable signs of concussion; loss of responsiveness, impact seizure, slow to get up, motor incoordination, rag doll appearance, blank/vacant look, clutching at head and facial injury (Makdissi & Davis, 2016a). Makdissi and Davis reported that some of these signs were reliable and valid for on-field recognition of concussive injury, but no particular sign was 100% reliable for a diagnosis and suggested they could be improved with clear definitions of each sign created, plus adequate quality of video feeds featuring multiple angles. A hierarchical flowchart ranking these observable signs of concussion in Australian Football was created with the goal of improving timely sideline diagnosis (Davis & Makdissi, 2016). The same checklist of observable video signs of concussion created specifically for Australian Football was later used in American Football to report the frequency, sensitivity, specificity and predicted value of these video signs in National Football League athletes (Elbin et al., 2020). In this study 26% of athletes diagnosed with concussion failed to show a video sign on review, showing the importance of sideline evaluation and revision of video signs checklists specifically for American Football.

Gardner and colleagues were the first to report the use of retrospective video analysis of medically diagnosed concussion in the sport of rugby league (Gardner, Iverson, Quinn, et al., 2015). Three professional clubs from the 2013 National Rugby League (NRL) season in Australia were reviewed to provide descriptive characteristics of concussive injuries. The incidence of concussion was 14.8 per 1000 player match hours and upon review three quarters of these incidents came from a high tackle. For the following 2014 NRL season a video analysis of the new HIA, which saw mandatory removal of any player suspected of sustaining a concussion, found that it was being used as intended when there was a suspicion of injury as many players who were removed and assessed were then cleared to return to play (Gardner et al., 2016). This study was expanded to include athletes from the corresponding 2014 National Youth Competition (under 20's) to also describe and compare match situational factors involving the use of the HIA, reporting similar findings (Gardner, Kohler, Levi, & Iverson, 2017).

Research into easily identifiable video signs of possible concussion is scarce with very little consistency across sporting codes with the interpretation of these signs. Gardner and colleagues, in their retrospective video analysis of the 2014 NRL season, determined the rates of six objective concussion signs throughout a full rugby league season (Gardner, Howell, et al., 2017). The six signs in this study included: clutching or shaking of the head, slow to return to feet/play, gait ataxia or "wobbly legs", blank or vacant stare, evidence of unresponsiveness and post-impact seizure. During the 2014 NRL season, these six video-identifiable signs were compared to SCAT3 findings along with return to play decisions (Gardner, Wojtowicz, et al., 2017) and also the use of the HIA and associated medically diagnosed concussions (Gardner, Howell, & Iverson, 2018). Davis and colleagues gathered an expert panel from seven national and international sporting codes to agree on six video identifiable signs that are most useful in identifying possible concussions and create consensus definitions for all six signs (Table 4) (Davis et al., 2019a). The presence of one sign does not create a diagnosis of a concussion and there may be other video signs that can occur but are non-specific (e.g., facial injury) or too difficult to assess on video (e.g., confusion/behaviour change). The identification of one or more of these signs suggests the need to remove the athlete from play and performance of a formal assessment and evaluation of concussion.

Table 4. Consensus definitions of video identifiable signs of possible concussion

Video Sign	Description
Lying Motionless	Lying without purposeful movement on playing surface for more than two seconds indicates the need for removal and further assessment of athlete. Depending on the circumstances, significantly longer periods of motionless may indicate the need for permanent removal from play
Motor Incoordination	Appears unsteady on feet (loss of balance, struggling to get up/falling over or staggering and stumbling), or in the upper limbs (fumbling).
Impact Seizure	Involuntary movements involving periods of asymmetric and irregular rhythmic jerking of axial or limb muscles
Tonic Posturing	Involuntary sustained contraction of one or more limbs, usually upper limbs, so that the limb is stiff despite the influence of gravity or player position. This can include cervical, axial, and lower limb muscles and has previously been described as "no protective action – stiff"
No Protective action - floppy	Falls to the playing surface without protecting themselves (i.e., not stretching out arms/hands to break fall) after a direct or indirect head knock. In the instance where a player's arms are being held by a tackling opponent this may be observed in the neck (cervical hypertonia)
Blank/vacant look	Player exhibits no facial expression or apparent emotion in response to the surrounding environment. This can include a lack of focus/attention of vision and best interpreted in reference to the athletes normal or expected facial expression

(Davis et al., 2019a)

Different professional sporting codes have implemented different strategies for in-game video analysis which can include a separate viewing area with broadcast feeds controlled by medical staff and dedicated concussion "spotters" trained in identifying video signs of concussion. It is essential spotters are adequately trained in their respective sports as proper interpretation of video requires the reviewer to understand the context of each injury. Each sport is required to be reviewed separately as differences between sports in field size and surface, number of players, protective equipment and video camera angles and distances can affect judgement (Davis & Makdissi, 2016; Davis et al., 2019b). Sideline review using the six consensus video observable signs has shown to be highly specific for detecting concussions, however attempting to identify concussion solely through video review is insufficient and should remain a supportive tool to clinical diagnosis (Gardner, 2021). Whilst now common in most professional sporting codes that carry a high risk of concussive injury, sideline video review is not a viable option for a large number of junior and amateur sporting competitions due to cost and availability of appropriate video cameras and trained medical personnel. Where possible, video review can help provide critical information to aid with the assessment of concussion, however the clinical diagnosis is still to be made by a doctor based on the assessment of symptoms.

1.3 Literature Review - Use of impact sensors and concussion

Impact sensors are a tool for measuring head kinematics in sport, with many studies reporting head impact exposures in a number of professional and non-professional competitions (O'Connor et al., 2017). When a force is applied to the skull, combined linear and angular accelerations cause strain and pressure on the brain parenchyma. Acceleration refers to the rate of change in velocity and once this reaches a currently unknown tolerable limit of brain tissue, a concussive injury occurs. The development and increasing availability of instrumentation that can measure these biomechanical forces has led to an influx of research with the goal of finding an injury threshold, as well as improving head protection and management of the concussed athlete accordingly. The availability of low-power, low-cost wearable accelerometers and helmet-mounted systems has seen an increase in both research and consumer use (Brennan et al., 2016; Wu, Nangia, et al., 2016).

The first published use of accelerometers to measure head impact data occurred during American collegiate football seasons in the early 1970's, with a suspension-fitted system keeping the accelerometer inside the helmet and close to the athlete's head (Moon, Beedle, & Kovacic, 1971; Reid, Epstein, O'Dea, Louis, & Reid, 1974). Using a single triaxial accelerometer, one player was followed across two seasons, with different players participating each season. From 650 recorded impacts there was a great variance in peak accelerations, ranging from 40g to 530g, and notably many impacts of greater magnitudes than the concussion producing impact (Reid et al., 1974). The introduction of this technology allowed for in-game analysis of head kinematics and paved the way for a new area of concussion research. Impact sensor research expanded to different sports in the early 2000's with a comparison study between American football, ice hockey and soccer (Naunheim, Standeven, Richter, & Lewis, 2000). This study incorporated a single triaxial accelerometer fitted into a helmet of one player from ice hockey and soccer and two football players (one offensive and one defensive). Due to helmets not being routinely used in soccer the methodology was slightly altered and data was not collected during a competitive match, but rather simulated play. This version of impact sensor technology used a battery-powered, self-contained unit fitted underneath shoulder pads and was only used on one or two players simultaneously limiting its value in large sample size research projects (Naunheim et al., 2000).

With the cost and size of accelerometer systems making them not applicable for widespread use, a need was identified for a smaller, wireless version suitable for large scale use. First described at the 27th American Society of Biomechanics Meeting in 2003, the first modern era style in vivo impact accelerometer aimed to solve this problem; the Head Impact Telemetry (HIT) system which incorporated six single-axis accelerometers fitted inside a football helmet (Greenwald, Chu, Crisco, & Finkelstein, 2003). The HIT system, whilst also much cheaper than other available triaxial accelerometers, allowed accurate measurement of linear and angular accelerations and were easily mountable in all helmeted sports. For the first time accelerometers were able to measure linear and angular acceleration magnitude and impact location and duration at an affordable cost whilst taking up minimal space inside the helmet (Crisco, Chu, & Greenwald, 2004; Williams, Dowling, & O'Connor, 2016). Pellman and colleagues, using nine accelerometers configured on a Hybrid III crash dummy similar to the six sensor configuration of the HIT system, collected laboratory data recreating game impacts and injuries (Pellman, Viano, Tucker, Casson, & Waeckerle, 2003). This study, utilising multiple sensors, was able to describe new variants of linear and angular accelerations that contribute to concussive impacts and paved the way for future research projects in real-time game scenarios.

The HIT system was first used in vivo during a 2003 American collegiate football team season, with a maximum of 8 players monitored simultaneously (Duma et al., 2005). The HIT system was validated with impact tests prior to use, which indicated a ±4% error for linear and angular accelerations. Each player was selected by medical staff and followed for a two-week period of games and practices. Accelerometers were spring mounted to maintain constant contact with the head and to ensure any measurements where true to the head, not helmet. The unit contained an on-board memory and wireless transceiver to transmit impact data to a sideline computer system in real time. Once an impact exceeded a pre-set threshold of 10g on any single accelerometer, a 40-millisecond waveform (12ms pre-trigger and 28ms post-trigger) of linear and angular accelerations was timestamped and sent to the sideline receiver (Duma et al., 2005). The study was expanded the following season, with up to 18 players from the same team able to be monitored and each player being followed for an entire season over the course of 22 games and 67 practices (Brolinson et al., 2006). Both studies incorporated the use of video to review injury mechanics of specific impacts but did not verify every impact recorded and highlighted the need for an increase in sample size and data collected, plus sensor monitored injury events to allow for more thorough conclusions.

This was the start of a large number of research projects utilising the HIT system, which led to an increase in available data from multiple age groups, competition levels and different collision or contact sports that carry a risk of concussive injury. Schnebel and colleagues, in 2005, compared head acceleration impacts from collegiate level American football athletes to that of High School American football athletes (Schnebel, Gwin, Anderson, & Gatlin, 2007). They reported that older, more experienced college athletes experienced higher impact accelerations than their younger, less experienced counterparts. In a separate study, Broglio and colleagues reported mean linear accelerations in high school athletes as higher than previously reported collegiate athletes (Broglio et al., 2009). Investigations from a number of American football high school and collegiate teams showed a statistically significant difference in impact magnitudes between playing positions and event types (Broglio et al., 2009; Crisco et al., 2011; Mihalik, Bell, Marshall, & Guskiewicz, 2007). Whilst specific to American football, this research highlights that an association exists between player position and the likelihood of sustaining high magnitude linear accelerations, which could translate to a large variety of sports. In a separate study on collegiate level American football players, McCaffrey and colleagues first reported the effects of impact magnitude on the performance of balance and neurocognitive function (McCaffrey, Mihalik, Crowell, Shields, & Guskiewicz, 2007). Players underwent preseason baseline testing and real-time acceleration data from the HIT system was split into high (>90g) and low (<60g) acceleration categories to compare post impact clinical outcomes. This initial study did not find a link between a single high magnitude impact and decreased balance and neurocognitive function performance but led the way for more research into the neurological effects of head impacts and tested the proposed theoretical injury thresholds (McCaffrey et al., 2007). The same hypothesis was tested in a similar study and observed no relationship between linear or angular acceleration magnitude and decreased balance and neuropsychological functioning (Guskiewicz et al., 2007). From a small sample of data, these findings suggested that clinical acute symptom severity, balance stability and neuropsychological function performance could occur from widely varying magnitudes of linear and angular accelerations. Subsequent investigations attempted to define; linear and angular thresholds and risk curves for concussive injury among a range of collegiate and high school American football teams (Broglio et al., 2010; Crisco et al., 2012; Funk, Rowson, Daniel, & Duma, 2012; Greenwald, Gwin, Chu, & Crisco, 2008; Guskiewicz & Mihalik, 2011; Rowson et al., 2012), frequency and location of impacts (Crisco et al., 2010; Crisco et al., 2011) and cumulative effects of multiple impacts across a full season (Broglio et al., 2011; Crisco et al., 2012).

Outside of American football, the HIT system was first utilised in ice hockey with a specific model created to fit inside a standard ice hockey helmet (Mihalik, Guskiewicz, Jeffries, Greenwald, & Marshall, 2008). A number of studies followed which described similar characteristics of playing position and cumulative effects reported to that of previous American football studies (Mihalik et al., 2012; Reed et al., 2010). The introduction of the

HIT system in ice hockey allowed for the first comparison study between male and female athletes, as both are played at the collegiate level, with reported impact frequency and magnitude higher in male athletes than females (Brainard et al., 2012; Wilcox, Beckwith, et al., 2014; Wilcox, Machan, et al., 2014). Further research expanded the use of the HIT system into boxing (Stojsih, Boitano, Wilhelm, & Bir, 2010), snow sports (Dickson, Trathen, Waddington, Terwiel, & Baltis, 2016) and a specific head band design was created for use in soccer where helmets are not commonly used (Hanlon & Bir, 2012). A different helmet based impact sensor, the GForce Tracker, has been used to monitor head impacts in male collegiate lacrosse athletes (Kindschi, Higgins, Hillman, Penczek, & Lincoln, 2017). This tracker consists of a single sensor attached with Velcro to the inner lining of a lacrosse helmet and contains a triaxial accelerometer and gyroscope to calculate linear accelerations and angular velocities. Laboratory testing of the device has determined large margins of error in raw sensor measures with more work needed to be done to characterise necessary adjustment factors for peak linear acceleration results before data collection (Allison, Kang, Maltese, Bolte, & Arbogast, 2015). In rugby league, and a large number of other contact and collision sports, players do not wear hard shelled helmets needed for the HIT or other helmeted impact sensor systems, with a small percentage of players choosing to wear a soft shelled helmet not suitable to house this technology. For the expansion of head kinematics research there was a need for the development of alternative designs that do not require a helmet.

An instrumented mouthguard accelerometer was created as an alternative to the helmet mounted systems previously used in an attempt to gain a direct assessment of the actual acceleration of the head and not the helmet (Higgins, Halstead, Snyder-Mackler, & Barlow, 2007). The mouthguard involves a triaxial linear accelerometer and triaxial angular rate sensor embedded in a plastic mouthpiece to compute head kinematics such as peak linear acceleration and peak angular acceleration (Siegmund, Guskiewicz, Marshall, DeMarco, & Bonin, 2016). It has been used in studies in American football (Camarillo, Shull, Mattson, Shultz, & Garza, 2013; Hernandez et al., 2015), rugby union (King, Hume, Brughelli, & Gissane, 2015), boxing (Hernandez et al., 2015) and mixed martial arts (Hernandez et al., 2015). Whilst it offers the ability for use in non-helmeted sports such as rugby union, rugby league and soccer it does have some drawbacks. The bulky design and need for individual customisation limit its ease of use and saliva build up can affect some of the activation contacts inside the mouthguard (King et al., 2015). Other factors such as mandible motion and variation in mouthguard design can affect performance and cause a problem in data collection (Wu, Nangia, et al., 2016).

The x-Patch™ head impact-sensor, an adhesive-mounted, six degree of freedom measurement device, was developed as an alternative to instrumented mouthguards to measure head impacts in non-helmeted sports. The lightweight, cost-effective and skin-mountable design of the x-Patch™ make it suitable for all contact sports, both helmeted and non-helmeted (O'Connor et al., 2017). The sensor, which is mounted using a single-use adhesive on the mastoid process behind the ear of the athlete, contains a triaxial accelerometer that measures linear acceleration in three planes, a triaxial angular rate sensor, a small 4.2V battery and on-board memory chip. When an impact event exceeds a linear acceleration reading of 10g the sensor is triggered and data is recorded for 100 milliseconds (10ms pre impact and 90ms post impact) with the sampling rates of 1000Hz for linear accelerations and 800Hz for angular velocity. Acceleration and rotational data recorded is transformed to calculate linear and angular accelerations and velocities at the centre of gravity of the head. (Chrisman et al., 2016; Tiernan, Byrne, & O'Sullivan, 2019). The x-Patch™ was first reportedly used in a study of female collegiate and high school soccer players (McCuen et al., 2015). Before utilising the x-Patch^{TM} in this study, McCuen and colleagues validated the sensor in a laboratory test by attaching it to a Hybrid III test dummy and applying impact loads using an instrumented mallet. Similar laboratory tests confirmed that the x-Patch^{TM} provides reasonable indication of linear acceleration but high levels of error for angular velocity and acceleration measurements (Tiernan et al., 2019; Wu, Laksari, et al., 2016). A number of studies followed, aiming to quantify and describe head impact exposures with the x-Patch^{TM} in soccer (Chrisman et al., 2016; Lynall et al., 2016; McCuen et al., 2015; Press & Rowson, 2017), American football (Reynolds et al., 2016a; Swartz et al., 2015; Yeargin, Kingsley, Mensch, Mihalik, & Monsma, 2018), lacrosse (Caswell et al., 2017; Cortes et al., 2017; Le et al., 2018; Reynolds et al., 2016b; Vollavanh et al., 2018), Australian rules football (King, Hecimovich, Clark, & Gissane, 2017), rugby union (King, Hume, Gissane, & Clark, 2016) and rugby league (King, Hume, et al., 2017; King et al., 2018).

The current literature in rugby league impact sensor studies is limited, with only two previous studies utilising the x-Patch^{TM} to quantify and describe head impacts at a junior and adult female's club level (King, Hume, et al., 2017; King et al., 2018). During a 2014 competition season in New Zealand, 19 junior club level rugby league players (age: 10 ± 1 years) were instrumented with x-Patch^{TM} sensors on the mastoid process behind their right ear. Over 12 matches, 1977 impacts were recorded over 10g, with each player recording a mean of 116 impacts ≥10g per season and 13 per match. King and colleagues reported higher mean impacts per player per match for forwards compared to backs (forwards = 15, backs = 9) but higher average linear accelerations for backs compared to forwards (forwards = 22g, backs = 23g). The sensor recorded the most impacts (48%) from the side of the head, followed by impacts from the front (26%), back (25%) and top (1%). A similar rugby league study, during a nine-game competition season, used the x-Patch^{TM} to quantify head impacts ≥10g from 21 female athlete’s (King et al., 2018). Similar to the previous rugby league study, the side of the head (48%) was the most common impact location, followed by the front (27%), back (23%) and top (2%). Each player recorded an average of 14 head impacts per match. Forwards recorded a higher number of mean total impacts (forwards = 17, backs = 12) but again had a lower average linear acceleration than backs (forwards = 14g, backs = 15g). This is a higher frequency of per-match averages for all players than the previous rugby league study at a junior club level. This can be attributed to a number of factors relating to style and speed of game play, size and ability of athletes (King et al., 2018).

The use of a secondary source to verify and analyse x-Patch™ recorded data is essential to validate all recorded impacts and to assess the characteristics of head impacts. A study of collegiate female soccer players found only 16% of total x-Patch™ recorded impacts ≥10g where visualised on video, which increased to 65.8% when the threshold was raised to 34g (Press & Rowson, 2017). A similar study using a 10g threshold on collegiate lacrosse players found 13% of all sensor recorded impacts were verified on video during games and practices for an entire season (Vollavanh et al., 2018). Cortes and colleagues utilised video review of x-Patch™ recorded impacts ≥20g in girls and boys high school lacrosse to ensure impacts occurred as a result of normal game-play. (Cortes et al., 2017). Video footage obtained using a high-definition camera positioned mid-field at the highest possible vantage point to capture all gameplay surrounding the ball was synchronised with timestamps of x-Patch™ recorded impacts. After filtering out impacts that occurred outside of normal game time (i.e., impacts before or after the first and final whistle), 65% of all impacts ≥20g were verified on video. The increased accuracy of verified impacts compared to other studies can be attributed to the use of only impacts recorded between game start and finish times and the increased threshold of 20g to remove low acceleration events as previously described. Caswell and colleagues used a similar methodology to verify head impacts ≥20g in girls high school lacrosse with the aim of describing these impacts based on player position, mechanism and game play characteristics (Caswell et al., 2017).

1.4 Thesis Objectives

This study will utilise the x-Patch™ impact sensor (X2 Biosystems; Seattle, WA)(see Fig. 1) and video review of game footage to record and analyse impacts in rugby league football at both a semi-professional and junior representative level. McCuen and colleagues, in the first published x-Patch™ study, determined that the sensor was sensitive enough to record low acceleration events in soccer, such as hard stops, cutting, hard kicks, in the 10g to 20g range. With events like these unlikely to result in neurophysiological damage it was suggested that the threshold for recorded head impacts be raised to 20g to eliminate these normal game-play events until neurocognitive-based assessments were merged with x-Patch™ data to prove an accurate threshold (McCuen et al., 2015).

No previous study has utilised video as a secondary source to verify and describe the characteristics of x-Patch™ recorded impacts in rugby league. Previous rugby league studies have included impacts ≥10g without video review to verify each recorded impact, leaving a possibility that false-positive head impacts have been included in the data set. There is a growing body of research combining head impact exposures recorded by the x-Patch™ with review of game video to verify the accuracy of wearable sensors. The current research highlights the need for a more complete assessment of the validity of all impacts to ensure the accuracy of recorded head impacts exposures. The primary aim of this study is to determine the reliability and accuracy of x-Patch™ recorded impacts ≥20g in rugby league at a men's semi-professional and junior representative level. Head impacts will be recorded across an entire season at each respective level and synchronised with video footage to remove all impacts outside of game play and to verify the remaining impacts. The secondary aim of this study is to describe playing characteristics and game-play situations of all video verified in-game impacts, whilst closely monitoring each player for any video identifiable signs of concussion.

Figure 5. x-Patch™ impact sensors as worn throughout this study

(Pandaram, 2015 #862)

Chapter 2: Publication 1

Verifying Head Impacts Recorded by a Wearable Sensor using Video Footage in Rugby League: a Preliminary Study

Carey, L., Stanwell, P., Terry, D.P. *et al.* Verifying Head Impacts Recorded by a Wearable Sensor using Video Footage in Rugby League: a Preliminary Study. *Sports Med - Open* **5,** 9 (2019)

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Abstract

Background: Rugby league is a full-contact collision sport with an inherent risk of concussion. Wearable instrumented technology was used to observe and characterize the level of exposure to head impacts during game play.

Purpose: To verify the impacts recorded by the x-Patch™ with video analysis.

Study Design: Observational case series

Methods: The x-Patch™ was used on eight men's semi-professional rugby league players during the 2016 Newcastle Rugby League competition (five forwards and three backs). Game day footage was recorded by a trained videographer using a single camera located at the highest midfield location to verify the impact recorded by the x-Patch™. Videographic and accelerometer data were time synchronized.

Results: The x-Patch™ sensors recorded a total of 779 impacts ≥20 g during the games, of which 732 (94.0%) were verified on video. In addition, 817 impacts were identified on video that did not record an impact on the sensors. The number of video-verified impacts ≥20 g, per playing hour, was 7.8 for forwards and 4.8 for backs (range = 3.9–19.0). Impacts resulting in a diagnosed concussion had much greater peak linear acceleration ($M = 76.1$ g, SD = 17.0) than impacts that did not result in a concussion ($M = 34.2$g, SD = 18.0; Cohen's $d = 2.4$).

Conclusions: The vast majority (94%) of impacts ≥20 g captured by the x-Patch™ sensor were video verified in semi-professional rugby league games. The use of a secondary source of information to verify impact events recorded by wearable sensors is beneficial in clarifying game events and exposure levels.

Keywords: Head impacts, Rugby League, Wearable sensors, Accelerometer, Video review

Key Points

- Wearable instrumented technology has the potential to quantify the kinematic responses of the head when exposed to head impact forces during contact and collision sports.
- The vast majority of high acceleration impacts (≥ 20 g) recorded on sensor were verified on video review of the games, and impacts resulting in a medically diagnosed concussion had greater peak linear acceleration than impacts that did not result in a concussion.
- There was a substantial number of possible false-positive high-acceleration impacts recorded on the sensors before, during, and after the games. It is recommended that until sensor technology improves, head impact sensor data are used in conjunction with video.

Background

Rugby league is a high-intensity collision sport [32] with a risk of concussive injury for participants [18]. Concussion can occur in rugby league through direct head impacts and potentially through indirect impacts, i.e., inertial or impulsive [44], because both can give rise to the necessary brain loadings considered to cause concussion. The incidence of medically diagnosed concussions in three clubs in the National Rugby League (NRL) was 14.8 and 8.9 per 1000 player match hours in 2013 [20] and 2014 [19], respectively. The incidence rate of suspected concussions based on use of the "concussion interchange rule" was 24.0 per 1000 NRL player match hours [21]. No study has reported on the incidence of concussion at semi-professional or amateur levels of competition [18]. Accurately and quickly identifying a concussion is especially important in the NRL, both for player safety and team strategy. If a player is evaluated for but not diagnosed with a concussion, the team is forced to use one of their 12 "interchanges," while if the player is diagnosed with a concussion, an interchange is not used.

Using technology to assist in identifying head impacts and concussion, diagnosis has been increasingly common. For instance, sideline video review and analysis has been introduced in a number of professional leagues worldwide to improve the recognition of a possible concussion [40]. Several studies have reviewed the usefulness and limitations of sideline and post-game video review [15,22,38,40]. For example, some studies evaluating video use in professional leagues [15,19,21,22,24,38,40,41] reported that video injury surveillance can be difficult to interpret, but may provide a useful adjunct to the recognition of concussion [6]. There has also been interest in examining whether impact sensors can identify head impacts. Impact sensors have been used in a number of research studies of helmeted (e.g., American football [4,5,6,7,11,16,26,29,52,54,56,61], ice hockey [45,46,47,57,58]), and non-helmeted sports (e.g., football/soccer [30,43], rugby union [34,36], rugby league [37], Australian rules football [33,55], lacrosse [49], mixed martial arts [31]) to the kinematic responses to forces applied to the head during participation in sports. The validity of these impact sensors has been examined in controlled laboratory studies [1,2,3,8,9,14,28,33,39,51,53,60], suggesting peak linear acceleration as measured by the x-Patch™ has reasonable agreement with the Hybrid III anthropomorphic test device (ATD) head-neck system, but the angular velocity measured by the x-Patch™ had much poorer agreement. The low sampling frequency of the x-Patch™ has been suggested to be a reason for the poor agreement [48]. Although numerous studies recorded the total number of impacts that occurred while players wore the sensors [27,28,31,32,33,35,40,46,55], few of the studies verified those impacts via video [31,49,59] or were not able to differentiate direct head impacts from indirect impacts.

A growing body of research has combined the use of impact sensors with game video to verify the accuracy of impacts recorded by this wearable technology. However, a more complete assessment of the validity of all impacts using additional sources of information is required [12,50]. For example, only 16% of recorded impacts were verified on video in a study of women's collegiate football (soccer) [50], 65% in boys high school lacrosse [12], and 32% in girls high school lacrosse [10], suggesting that the wearable sensor technology may substantially overestimate impact events [13]. Few studies have examined rugby league using these technological advances. Gardner and colleagues [21] reviewed video footage of concussions and suspected concussions in the NRL. They reported that 98% of initial (primary) impacts occurred to the head/face, but they did not localize the impact location any further. More recently, King and colleagues [37] reported a total of 1977 impacts in 88 h of game play during a single season of junior rugby league using the x-Patch™ sensor, with 48% of impacts reported to have occurred to the side of the head, 26% to the front of the head, and 25% to the back of the head. However, every event (>10g) captured by the x-Patch™ sensor will be deemed to be a direct head impact and assigned a location on the head, regardless of whether such an impact occurred. No previous studies have combined video analysis and impact data from sensors in rugby league. The primary aim of this study was to determine the reliability of x-Patch™ derived measurements of head impact exposures. A secondary aim was to describe the playing characteristics and game play situation of the video-verified impacts in semi-professional men's rugby league.

Methods

Participants

Data were prospectively collected from a men's semi-professional rugby league team during the 2016 Newcastle Rugby League season. A total of 8 players (mean age 25.5 years, SD 4.7 years) from a single club consented to participate. The participant's playing position consisted of five forwards and three backs. A typical rugby league team formation involves 13 players (7 backs, 5 forwards) on the field at one time. During the course of the season, there were six medically diagnosed concussions in four players. Concussion was diagnosed by a medical practitioner. The operational diagnosis was consistent with the Concussion in Sport Group (Berlin, 2016) [42] definition. The research protocol was approved by the University of Newcastle Human Research Ethics Committee (reference no. H-2015-0323). The study was also endorsed by the Newcastle Rugby League and the participating club.

Measures

Impact Sensors

All consenting participants wore x-Patch™ sensors (X2 Biosystems) during all games that they participated in during the 2016 Newcastle Rugby League season. The x-Patch™ sensors were attached to the skin covering the right mastoid process of each player because previous literature has suggested that sensor positioning over the mastoid process is crucial to ensure that it is not activated by soft tissue effects during impacts [60]. Each sensor was uniquely labelled and applied to the players by a trained member of the research team in the change rooms. Sensors were affixed and activated before the team's warm-up, approximately 30 min before the beginning of the game. An alcohol wipe was used to clean the skin behind the ear over the right mastoid process before a Convacare protective barrier wipe (ConvaTec Inc.) was applied to help with adhesion of the area. The sensor was attached using a double-sided adhesive patch and worn for the entire game.

The x-Patch™ contains a triaxial accelerometer and gyroscope that measure linear and angular kinematics. These are applied to estimate the head's kinematic responses, e.g., resultant linear acceleration and peak linear acceleration (PLA), peak rotational velocity and acceleration (PRV), and location of impact. The slope of the relationship between the actual PLA in a laboratory setting and the PLA measured by the x-Patch™ has been reported as 0.972, which is similar to the expected relationship of 1.0 ($p = .14$) [53]. However, the relationship between the actual peak angular acceleration (PAA) and the measured (PAA) was only 0.7745 ($p = .0027$), which is statistically different from the expected 1.0 relationship. Therefore, we decided to not report in detail the angular head kinematic data (i.e., angular velocity and angular acceleration). The x-Patch™ does not measure impact force and cannot differentiate between a direct head impact and an impact to another part of the body that results in acceleration of the head, i.e., impulsive or inertial loading. The x-Patch™ records data when linear acceleration exceeds 10g; at which point, the x-Patch™ saves 10ms prior to the impact and 90ms after, with a maximum of 1000 data points per channel. During the study, each x-Patch™ was removed immediately after each game in the change room, and data were downloaded to the Injury Management Software (IMS; X2Biosystems). The IMS produces a time-stamped line output for each “impact” which included PLA, PRA, PAV, HIC, and other variables. The x-Patch™ does not measure impact force, and therefore, any perturbation of the wearer that causes a linear head acceleration greater than 10 g is recorded as a “head impact,” even when direct head impact did not occur. The sensors were cleared of data before being charged and stored for the next game.

Video Review

Each game was digitally recorded by a trained videographer. One single-view high-definition camera was positioned at the highest possible vantage point at the field’s midline (i.e., the centre). Close-up shots panned left and right following the ball to maximize the visibility of game play, players, and potential impacts. Game footage was analysed in conjunction with data obtained from the x-Patch™. Video time was synchronized with time stamps from the sensors using the first three impacts from each player. Each half of the game was viewed from start to finish using QuickTime X (Apple Inc.) by one author (LC). The reviewer has experience in watching professional rugby league. Video was played back at an appropriate speed to verify whether or not an impact occurred. This consisted of pausing, replaying, and using slow motion as needed. Every impact on video was matched to the sensor data for validation. An impact was defined as “any contact, to the head or trunk/torso, made to the player wearing an x-Patch™ by another player or the playing surface.” Sensor-recorded impacts not verified with video were identified. Similarly, impacts on video that did not correlate with x-Patch™ recorded impacts were identified. Impacts were categorized as either direct (defined as an impact that made direct contact with the head) or indirect (defined as an inertial or impulsive impact from contact made to the body rather than directly to the head). Impacts were also characterized by play characteristics (i.e., *attacking*—running with the ball, *defending*—tackling, and *off-the-ball incidents*—no player was in possession of the ball when contact between players was made). They were also characterized into number of tacklers (i.e., 1–4), wrestling impacts that happen after the initial contact (yes/no), side of contact (i.e., left, right, back, or front on), area of contact (i.e., head, shoulder, chest, arm, waist, or below), and whether an impact appeared to be direct contact with the sensor (yes/no). The type of game-play scenario was also considered. As previously described in the video review of rugby league game play [22], the "hit-up" was defined as "a type of play where the ball carrier charges directly into an organized defensive line." Data were coded in Microsoft Excel.

Statistical Analyses

Descriptive statistics (i.e., frequencies, percentages, medians, IQRs, and standard deviations) of peak linear acceleration (PLA) and peak rotational velocity (PRV) for all verified head impacts ≥20g were calculated by player position and game-play situation. Similar to criteria applied in previous studies [10,43], the review of impacts was limited to ≥20g to remove low acceleration events (< 20g) commonly associated with physical activities of game play (e.g., jumping, hard stops, sharp changes of direction) and unlikely to result in deleterious neurophysiological changes. Impact rates per player game hours (PGH) with corresponding 95% confidence intervals (CIs) were constructed. The impact rate was calculated as the number of verified impacts divided by the number of PGH. The formula for calculating the impact rate is provided below.

$$\text{Impact Rate} = \frac{\sum \text{Verified impacts} \geq 20g}{\sum \text{PGH}}$$

Players engaged in game play for different amounts of time over the course of the season. We calculated verified impacts per minute. Cross tabulations were conducted between the impact sensors' estimated head impact location and the characterization conducted using video analysis. Data were also reviewed for playing position (i.e., forward versus back) and play characteristics (i.e., attacking, defending, off-the-ball). An exploratory *t* test was used to compare the rate that forwards and backs sustained verified impacts. Exploratory analyses compared the acceleration (i.e., PLA) between verified/non-verified impacts, direct/indirect impacts, and concussion/non-concussion impacts using non-parametric tests because PLA was not normally distributed. The Mann-Whitney (MW) test was used when there was homogeneity of variances, and the Kolmogorov-Smirnov (KS) test was used when variances were unequal. All analyses were performed using SPSS 23 (IBM Corp.).

Results

Impact Frequency

During the 2016 Newcastle Rugby League competition, eight participants were instrumented with the wearable sensors and game video was captured during all games. These athletes played a total of 91 games across the season (89.1 player game hours/5346 player game minutes). Stratified by playing position, data from forwards accounted for 39.6% (2117 min) and data from backs accounted for 60.4% (3229 min) of playing time. The x-Patch™ became detached from each player at least once during the season, for a total of 183 min of lost data due to detached sensors for the season (backs $M = 19$ min, SD = 16.46, range = 15–50; forwards $M = 12$ min, SD = 19.38, range = 2–51). In addition, there was a 135-min game time lost due to faulty sensors (all forwards).

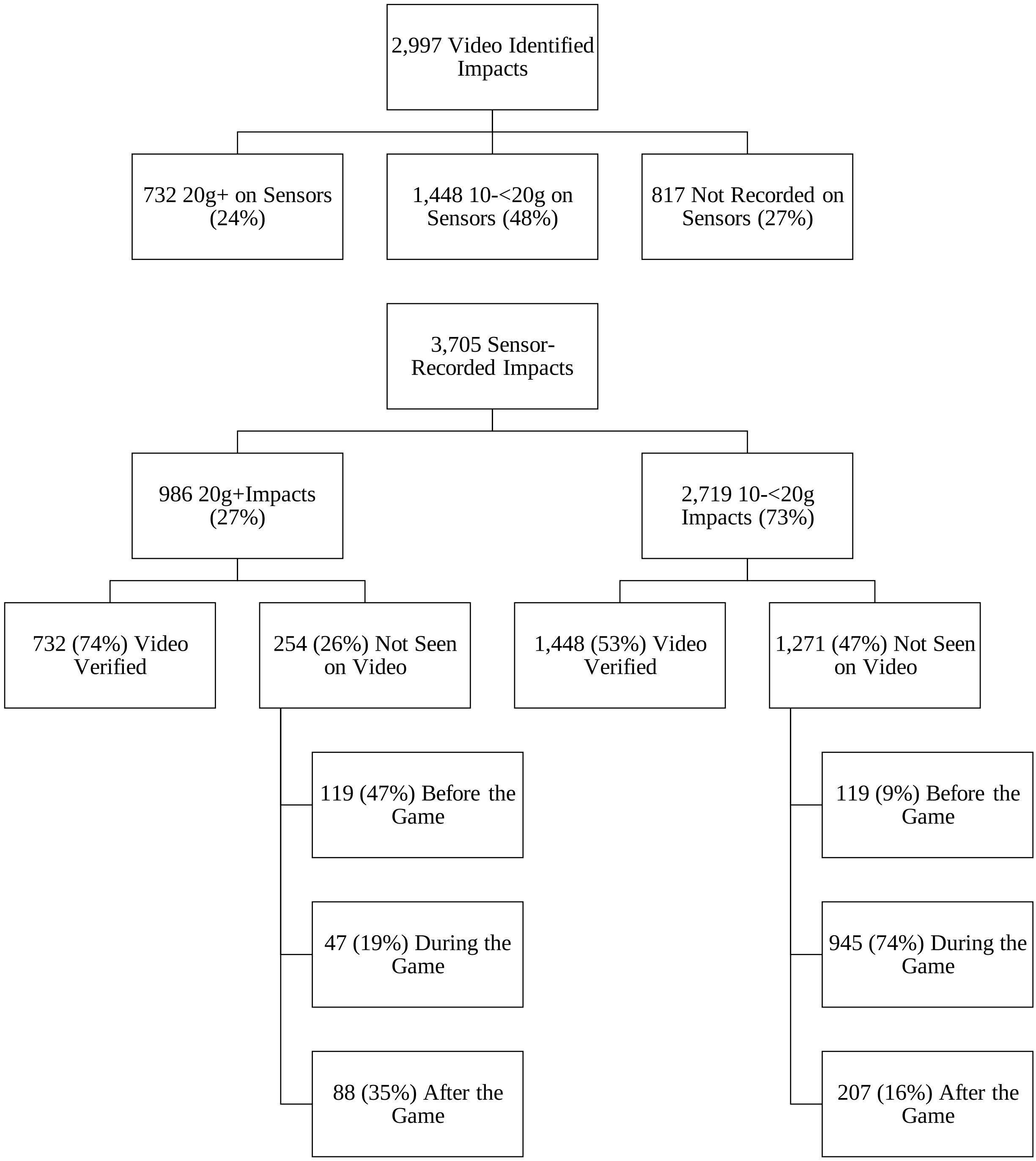
There were 2997 *video-verified* impacts to the eight players (Table 1). Of those, 732 were recorded as 20g or greater (24%), 1448 video-verified direct and indirect impacts were recorded as between 10g and 20g (48%), and 817 (27%; 36 direct vs 781 indirect) were not recorded on the sensors (see Fig. 1). The video review revealed 36 direct head impacts (24 to the side of the head, 6 to the front, and 6 to the back) that did not result in any data being recorded on the x-Patch™, in addition to 21 impacts (registered as >30g) recorded by the x-Patch™ that were not verified on video. There was no significant difference in the PLA of video-verified versus non-video-verified impacts (verified $M = 34.5$, SD = 18.3; non-verified $M = 41.2$, SD = 29.2; KS $Z = 0.96$, $p = .32$; Cohen's $d = -0.27$).

There were 3705 *sensor-recorded* impacts to the 8 players (see Fig. 1). Of those, 1525 (41.2%) were not seen on video. Of the 1525 impacts that were not seen on video, 533 (35.0%) occurred before or after the game. Interestingly, there were 254 impacts registered as ≥20g that were not seen on video, and of those, 119 occurred before the game (47%, presumably during warm up), 47 occurred during the game (19%), and 88 occurred after the game (35%). It seems particularly unusual that there would be 88 ≥20g impacts and 207 10 to 20g impacts to these 8 players occurring after the game had ended.

Table 1 Frequency of video-verified impacts by game time and playing position

		Video Verified		Sensor Recorded 10g+		Sensor Recorded 10g to <20g		Sensor Recorded ≥20g		Sensor Recorded and Video Verified ≥20g		Sensor Recorded and Video Verified 10g to <20g	
	Playing hours (mins)	Game Impacts (n)	Impacts per game hour (n)	Game Impacts (n)	Impacts per game hour (n)	Game Impacts (n)	Impacts per game hour (n)	Game Impacts (n)	Impacts per game hour (n)	Game Impacts (n)	Impacts per game hour (n)	Game Impacts (n)	Impacts per game hour (n)
1st Half	44.6 (2,673)	1,545	34.6	1,632	36.6	1,249	28.0	383	8.6	370	8.3	768	17.2
2nd Half	44.6 (2,673)	1,452	32.6	1,540	34.5	1,144	25.7	396	8.9	362	8.1	680	15.2
Forwards	35.3 (2,117)	1,716	48.6	1,323	37.5	902	25.6	421	11.9	407	11.5	798	22.6
Backs	53.8 (3,229)	1,281	23.8	1,849	34.4	1,491	27.7	358	6.7	325	6.0	650	12.1
Total Sample	89.1 (5,346)	2,997	33.6	3,172	35.6	2,393	26.9	779	8.7	732	8.2	1,448	16.3

Figure 1 Flow diagram comparison of video-identified impacts and sensor-recorded impacts



Direct Head Impacts by Game and Player Characteristics

Of the 732 video-verified impacts, 536 were identified as direct head impacts. Of the 536 video-verified direct head impacts, the ball carrier (attacker) recorded 261 (48.7%) and the tackler (defender) recorded 253 (47.2%), while 22 were recorded during an off-the-ball incident (4.1%; incidental contact $n = 9$; contact with the playing surface $n = 4$; melee/scuffle or fighting $n = 6$; contact celebrating tries $n = 3$). The number of impacts recorded in the first half (49.3%) compared to the second half of games (50.7%) was similar. Players sustained an average of 0.10 direct impacts per minute played (SD = 0.07, range = 0.04–0.27), which equates to an average of one verified impact per 10.0 min. Forwards sustained more verified impacts per minute compared to backs (forwards $M = 0.13$, SD = 0.08, 1 per 7.2 min; backs $M = 0.08$, SD = 0.03, 1 per 13.3 min). An exploratory independent sample t test suggests that forwards and backs did not statistically differ in the rate they sustained direct impacts ($t(7) = 1.04$, $p = .33$). However, effect size analysis shows a large, meaningful difference between the rates they sustained impacts based on playing position (Cohen's $d = 0.83$). The individual player data by playing position, game time impact, and video verification are provided in Table 2.

Table 2 Cross tabulation of frequency of verified in-game impacts measured by the x-Patch™, video-verified impacts, player position, and game time

	Playing Position	Player Time in Game (Mins)	Sensor-Recorded In-Game Impacts	Video Verified Game Impacts	Percentage of Impacts Verified	Video Verified Impacts per Game Hour	Video Verified Direct Impacts	Video Verified Direct Impacts per Game Hour
Player 1	Forward	365	29	29	100%	4.8	15	2.5
	Back	687	62	53	85.5%	4.6	41	3.6
Player 2	Forward	259	63	62	98.4%	14.3	27	6.3
Player 3	Back	1,120	73	73	100%	3.9	49	2.6
Player 4	Forward	568	182	180	98.9%	19.0	155	16.4
Player 5	Back	808	126	105	83.3%	7.8	85	6.3
Player 6	Forward	505	74	68	91.9%	8.1	44	5.2
Player 7	Back	614	97	94	96.9%	9.2	67	6.5
Player 8	Forward	420	73	68	93.2%	9.7	53	7.6
Total		5,346	779	732	94.0%	8.2	536	6.0

Note. Season Totals. Player 1 played in both forward and back positions during the season. Sensor recorded impacts were ≥20gs.

Impact Mechanism and Location

When stratifying all video-verified direct head impacts ($n = 536$) by the location of impact from the x-Patch™, the most impacts occurred to the front ($n = 190$, 35.4%) and side ($n = 194$, 36.2%), with fewer to the back ($n = 121$, 21.3%) and top ($n = 31$, 5.3%) of the head. When examining the location of the verified impacts on video review, the most impacts were determined to occur to the side ($n = 498$, 92.9%) and front ($n = 27$, 5.0%%), with fewer impacts to the back ($n = 11$, 2.1%). The x-Patch™ accurately recorded the location of video-verified direct head impacts in 55.6% of video-verified impacts to the front of the head, 38.0% of video-verified impacts to the side of the head, and 54.5% of video-verified impacts to the back of the head. The sensor recorded 39 impacts to the top of the head, whereas no impact was verified by video review as impacting the top of the head (see Table 3).

Table 3 Video-verified impacts: location accuracy of direct and indirect impacts

	Total				Direct Impact				Indirect Impact			
	x-Patch™ (n)	Video (n)	Agreement (n)	Accuracy (%)	x-Patch™ (n)	Video (n)	Agreement (n)	Accuracy (%)	x-Patch™ (n)	Video (n)	Agreement (n)	Accuracy (%)
Front	273	134	56	41.8	190	27	15	55.6	83	107	41	38.3
Side	264	582	228	39.2	194	498	189	38.0	70	84	39	46.4
Back	156	16	7	43.8	121	11	6	54.5	35	5	1	20
Top	39	0	0	0	31	0	0	0	8	0	0	0
Total	732	732	291	39.8	536	536	210	39.3	196	196	81	41.3

Direct impacts (as determined by video review) had a greater PLA compared to indirect impacts (direct $M = 37.59$, SD = 20.09; indirect $M = 26.22$, SD = 7.67; KS $Z = 4.14$, $p < .001$, $d = 0.75$), as well as greater PRV compared to indirect impacts (direct $M = 27.70$, SD = 11.55; indirect $M = 21.97$, SD = 9.02; KS $Z = 2.77$, $p < .001$, $d = 0.55$). Secondary impacts during a tackle (i.e., impacts after the initial contact) accounted for 261 (35.7%) of total impacts (Table 4). There were 580 tackles that resulted in the 732 video-verified impacts. For 480 tackles, there was 1 impact recorded; for 83, there were 2 impacts recorded; for 15, there were 3 impacts recorded; and for 2, there were 4 impacts recorded. There were additional 32 tackles occurring off the ball that resulted in 33 video-verified impacts (31 with 1 impact recorded and 1 with 2 impacts). The hit-up was a play that accounted for approximately 52% ($n = 301$) of all x-Patch™ recorded events. Of the hit-up plays, forward positions accounted for 44% ($n = 132$) of those impacts, while backs accounted for approximately 56% ($n = 169$) of impacts. A summary of the total impacts per play and the total impacts per play for forward and back positions is provided in Table 4.

Diagnosed Concussions

There were six diagnosed concussions during the season. All six concussions (100%) occurred as a result of a direct head impact. The PLA of the impacts that resulted in a diagnosed concussion was much greater ($M = 76.1$g, SD = 17.02, range = 61.6–106.6g) than video-verified direct impacts that did not result in a concussion that were > 20 g ($M = 34.20$g, SD = 17.96; MW $U = 183.50$, $p < .001$, $d = 2.39$). Figure 2 shows the PLA and PRV for all video-verified impacts with the six concussions highlighted.

Table 4 Total x-Patch™ recorded impacts per play

Impacts Recorded Type of Play	One Hit-Up	One Tackle	Total	Two Hit-Up	Two Tackle	Total	Three Hit-Up	Three Tackle	Total	Four Hit-Up	Four Tackle	Total	1 Off the Ball	2 Off the Ball	Total
Week 1	26 (10, 16)	15 (7, 8)	41 (17, 24)	7 (4, 3)	1 (1, 0)	8 (5, 3)	0	0	0	0	0	0	2 (1, 1)	0	2 (1, 1)
Week 2	18 (8, 10)	17 (15, 2)	35 (23, 12)	1 (0, 1)	1 (1, 0)	2 (1, 1)	0	0	0	0	0	0	1 (0, 1)	0	1 (0, 1)
Week 3	9 (5, 4)	30 (23, 7)	39 (28, 11)	1 (1, 0)	2 (0, 2)	3 (1, 2)	0	0	0	0	0	0	1 (1, 0)	1 (0, 1)	2 (1, 1)
Week 4	24 (11, 13)	32 (28, 4)	56 (39, 17)	4 (2, 2)	6 (5, 1)	10 (7, 3)	0	1 (1, 0)	1 (1, 0)	0	0	0	2 (0, 2)	0	2 (0, 2)
Week 5	11 (6, 5)	15 (11, 4)	26 (17, 9)	5 (3, 2)	2 (2, 0)	7 (5, 2)	1 (1, 0)	1 (0, 1)	2 (1, 1)	2 (1, 1)	0	2 (1, 1)	2 (0, 2)	0	2 (0, 2)
Week 6	22 (10, 12)	30 (19, 11)	52 (29, 23)	6 (2, 4)	8 (6, 2)	14 (8, 6)	0	1 (1, 0)	1 (1, 0)	0	0	0	4 (2, 2)	0	4 (2, 2)
Week 7	14 (7, 7)	16 (15, 1)	30 (22, 8)	4 (2, 2)	1 (1, 0)	5 (3, 2)	1 (0, 1)	0	1 (0, 1)	0	0	0	3 (1, 2)	0	3 (1, 2)
Week 8	28 (17, 11)	7 (4, 3)	35 (21, 14)	2 (1, 1)	2 (2, 0)	4 (3, 1)	3 (1, 2)	1 (1, 0)	4 (2, 2)	0	0	0	3 (0, 3)	0	3 (0, 3)
Week 9	10 (5, 5)	14 (5, 9)	24 (10, 14)	4 (1, 3)	1 (1, 0)	5 (2, 3)	1 (0, 1)	0	1 (0, 1)	0	0	0	2 (0, 2)	0	2 (0, 2)
Week 10	9 (1, 8)	4 (1, 3)	13 (2, 11)	2 (0, 2)	0	2 (0, 2)	0	0	0	0	0	0	2 (0, 2)	0	2 (0, 2)
Week 11	13 (1, 12)	5 (3, 2)	18 (4, 14)	2 (0, 2)	1 (0, 1)	3 (0, 3)	0	0	0	0	0	0	3 (0, 3)	0	3 (0, 3)
Week 12	20 (10, 10)	7 (4, 3)	27 (14, 13)	3 (1, 2)	2 (0, 2)	5 (1, 4)	1 (0, 1)	0	1 (0, 1)	0	0	0	1 (0, 1)	0	1 (0, 1)
Week 13	9 (4, 5)	10 (3, 7)	19 (7, 12)	0	0	0	1 (1, 0)	0	1 (1, 0)	0	0	0	2 (1, 1)	0	2 (1, 1)
Week 14	7 (4, 3)	15 (13, 2)	22 (17, 5)	2 (1, 1)	5 (5, 0)	7 (6, 1)	0	1 (0, 1)	1 (0, 1)	0	0	0	2 (1, 1)	0	2 (1, 1)
Week 15	13 (3, 10)	13 (12, 1)	26 (15, 11)	3 (2, 1)	3 (2, 1)	6 (4, 2)	0	0	0	0	0	0	0	0	0
Week 16	8 (3, 5)	9 (9, 0)	17 (12, 5)	2 (1, 1)	0	2 (1, 1)	2 (2, 0)	0	2 (2, 0)	0	0	0	1 (1, 0)	0	1 (1, 0)
Total	241 (105, 136)	239 (172, 67)	480 (277, 203)	48 (21, 27)	35 (26, 9)	83 (47, 36)	10 (5, 5)	5 (3, 2)	15 (8, 7)	2 (1, 1)	0	2 (1, 1)	31 (8, 23)	1 (0, 1)	32 (8, 24)
Average/Week	15.1 (6.6, 8.5)	14.9 (10.8, 4.2)	30 (17.3, 12.7)	3 (1.3, 1.7)	2.2 (1.6, 0.6)	5.2 (2.9, 2.3)	0.6 (0.3, 0.3)	0.3 (0.2, 0.1)	0.9 (0.5, 0.4)	0.1 (0.1, 0.1)	0	0.1 (0.1, 0.1)	1.9 (0.5, 1.4)	0.1 (0, 0.1)	2 (0.5, 1.5)

Note: Data in the parentheses are for forwards and backs, as follows: (forwards, backs).

Figure 2 Scatterplot of video-verified impacts by the x-Patch™

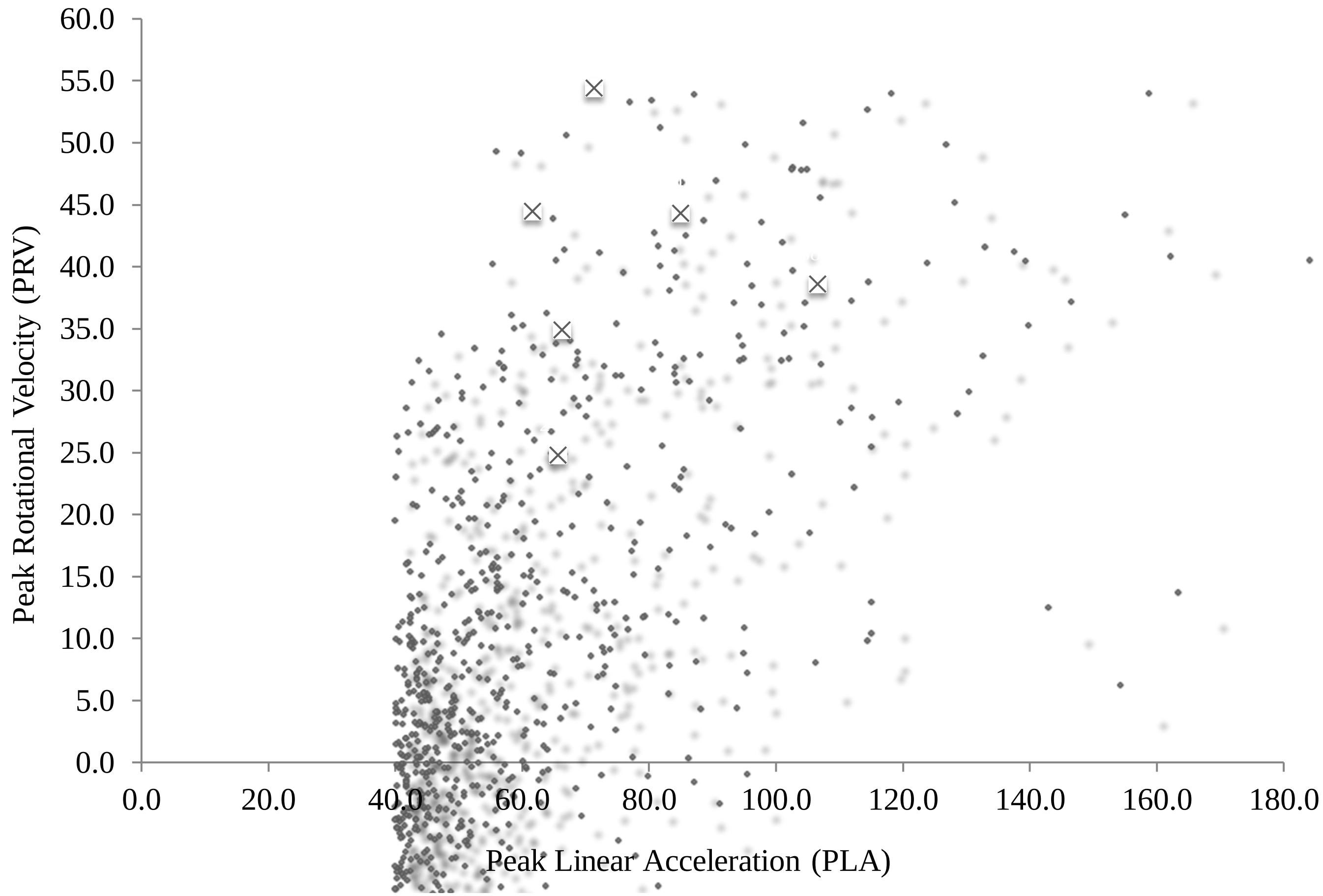


Figure Legend. X: medically diagnosed concussion impacts.

Discussion

The purpose of this study was to verify the information recorded by wearable impact sensors to determine the reliability of the data, in addition to describing the playing characteristics and game-play situation of the video-verified impacts in semi-professional men's rugby league. Eight semi-professional male rugby league players wore wearable impact sensors during a single season. The vast majority of high acceleration impacts during games were verified on video. Specifically, there were 779 in-game sensor-recorded impacts ≥20g, of which 732 were verified on video (i.e., 94%; Table 2). Differences in the number of video-verified impacts per hour of playing time were observed based on playing position, such that forwards had greater exposure compared to backs, consistent with previous literature [17,25]. As seen in Fig. 2, impacts resulting in a medically diagnosed concussion had much greater peak linear acceleration (M = 76.1g, SD = 17.0) than impacts that did not result in a concussion (M = 34.2g, SD = 18.0; d = 2.39). However, as seen in Fig. 2, there were six (0.82%) video-verified direct head impacts above the highest recorded concussion PLA, and 53 (7.2%) video-verified direct head impacts above the lowest recorded concussion PLA, that did not result in concussion - suggesting a host of factors beyond the impact acceleration may contribute to acute neurological disturbances of concussion.

There were 817 tackles or impacts on video review that did not result in any recording at all on the impact sensor (i.e., false negatives). It is difficult to determine the true level of false-negative data because video review does not enable determination of the observed impacts to the head that occur above or below the 10g threshold (i.e., which impacts are at a sub-threshold and do not register on the x-Patch™). In addition, given that for 101 (17%) tackles, there was more than 1 impact (i.e., in a single tackle, multiple impacts were recorded) registered by the x-Patch™, the true level of false-negative data could also be much greater than the 817 because on video review, it was only the initial impact that was considered as being missed, and not any subsequent impact that may have been recorded during the same tackle.

Our reported rate of video-verified true sensor-detected impacts may be an overestimate, and it might be confounded by player position. Rugby league is a demanding physical contact game with frequent body contact. Defensive players and “hit-up” players (i.e., forwards) may have a greater body contact rate than backs. If the x-Patch™ records spurious head impact events, as appeared to be the case before and after match play, by chance, the video review is likely to identify an impact event (i.e., some body contact) when the x-Patch™ records a spurious head impact. Rugby league may not be the ideal setting for validating all characteristics of head impact sensors. The rate of false-positive sensor-detected impacts cannot be determined. There were 295 impacts recorded on the sensors after the game had ended. Of those, 88 were ≥20g impacts. It seems unusual that there would be so many large impacts recorded after the game, and we cannot determine the extent to which the sensors yield false-positive findings before, during, or after the game. In general, the rate of false-positive impacts, in addition to the possibility that the device could register greater linear acceleration than was actually the case, *raises concern that impact sensor studies that do not verify impacts may be over-reporting both the level of exposure of athletes* (i.e., *the number of true head impacts*) *and the severity of the head impacts* (i.e., *the magnitude of the head’s kinematic responses*).

On average, players sustained 1 verified impact every 10.0 min. The rate that these athletes sustained impacts appeared to differ based on their playing position, with forwards sustaining impacts more frequently than backs. Our exploratory (and underpowered) independent sample t test did not show group differences, but this non-significant finding is likely an artifact of the small sample size in our pilot study; effect size analysis showed a large, meaningful difference in the number of impacts stratified by playing position (Cohen's $d = 1.15$). We have previously reported that the concussion interchange rule (a rule used by club medical staff to remove and assess a player suspected of having sustained a concussion to determine the player's suitability to remain in a game or be permanently removed) was used more commonly in forwards than in backs at the professional level (forwards 57%, backs 43%) [21] and the national youth level (forwards 66%, backs 34%) [22]. In the current study of semi-professional rugby league players, the impact exposure levels (as measured by the x-Patch™ and verified on video) revealed the forward positions are more commonly exposed to contact with the head during match play than the backline positions.

On-field play characteristics may also be associated with head impacts and potential concussions. A prior study showed that the concussion interchange rule was used to remove the tackler 55% and 61% of the time compared to 43% and 38% for the ball carrier at the professional and national youth level, respectively [22]. In the current study, approximately 44% of the video-verified impacts involved the tackler, approximately 51% involved the ball carrier, and approximately 5% were recorded during an off-the-ball incident. A tackler making an upper body tackle high on the ball carrier making a hit-up was the most common play leading to the use of the concussion interchange rule, accounting for 26% of all uses at the professional level [21]. In the current study of semi-professional rugby league players, the hit-up play accounted for approximately 49% ($n = 301$) of all verified x-Patch™ recorded impacts, with the tackler accounting for 46% ($n = 279$) and 5% ($n = 32$) coming from off-the-ball incidents, a similar result as the professional level. In addition, the hit-up play data revealed that forward positions accounted for 44% (n = 132) and backs approximately 56% (n = 169) of impacts recorded.

The current study offers some insights into the level of impacts sustained in the sport of rugby league at the semi-professional level. Although the results are preliminary given the small sample size, it is clear that there appears to be variations in impact exposure by position (forwards versus backs), type of play (i.e., the hit-up), game situation (ball carrier versus tackler), and number of tacklers involved in a tackle. These findings also offer further insights into the previous rugby league video analysis studies that have been conducted at the professional level [19,20,21,22,23] examining risks for activation of a head injury assessment (HIA) and subsequent diagnosed concussion.

In the current study six concussions were diagnosed in players wearing the x-Patch™. There was a large, statistically significant difference between the PLA of concussive impacts versus non-concussive impacts. Future studies should aim to collect a larger number of concussion events in order to calculate the possible thresholds of PLA (as well as other parameters) and sensitivity and specificity of those impact thresholds to determine the potential clinical application of the x-Patch™ or similar devices for assisting in the clinical diagnosis of concussion.

There are a few limitations to the current study design. First, using only eight players is a small sample size and limits the generalizability of the findings. Second, the false-negative incidences only considered a single (i.e., initial) impact as missing, as such, the possibility that a second or subsequent impact registration was also not coded by the impact sensor was not calculated as a "missed impact" resulting in an underestimation of the potential false negatives. Third, each video was coded by a single researcher. It is possible that some impacts were missed by the researcher when reviewing video. Fourth, the current findings may not be generalizable to all levels of rugby league or other sports. Fifth, the current findings are limited to the x-Patch™ impact sensor only and may not reflect the capabilities of other impact sensors. Finally, there is no accepted standard as to what head impact-related PLA represents a "subconcussive" hit (e.g., 10 to 20g) apart from a strict clinical outcome, nor is it understood how or whether these impacts affect brain microstructure or function. Future studies with larger sample sizes may consider reviewing the role cumulative impacts may have on the vulnerability of an athlete to future concussive events. In addition, in view of the literature that suggests that cumulative head impact exposure is a predisposing factor for the onset of concussion [27,55], reviewing the potential increased vulnerability for subsequent concussions in athletes who sustain multiple impacts and multiple concussions may also be an important focus in future larger studies. It may also be useful for future studies to extend video recordings to before and after the match so that non-match play head impacts can be better understood.

Conclusion

These data are consistent with the findings from Cortes and colleagues [13] who found that using a secondary source of information to verify head impact events recorded by wearable sensors was beneficial in clarifying game events. Similar to those boys and girls lacrosse players [13], a considerable number of false-positive head impacts were recorded by the wearable sensors in our semi-professional rugby league players. This illustrates the value of adding an additional source of information (i.e., video) when quantifying the impacts players sustain. The implementation of a standard verification method could assist in validating data and reducing false-positive rates. It is important that these false-positive results are described appropriately in impact sensor studies to more accurately communicate the findings of impact sensor research [13] and better brain loading patterns, and inform scientists/industry leaders about the limitations of current wearable technology. Such findings have practical implications for how impact sensors should be used and how existing data should be interpreted. Video confirmation of impacts and time synchronization can support a more accurate measure of impact frequency/magnitude and characterization of head impact events [13]. The use of a secondary source to verify impacts will assist in clarifying the severity of the impacts and the level of burden of exposure for an athlete.

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Chapter 3: Publication 2

Video Analysis and Verification of Direct Head Impacts Recorded by Wearable Sensors in Junior Rugby League Players

Carey, L., Terry, D.P., McIntosh, A.S. *et al.* Video Analysis and Verification of Direct Head Impacts Recorded by Wearable Sensors in Junior Rugby League Players. *Sports Med - Open* **7,** 66 (2021)

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Abstract

Background: Rugby league is a high-intensity collision sport that carries a risk of concussion. Youth athletes are considered to be more vulnerable and take longer to recover from concussion than adult athletes.

Purpose: To review head impact events in elite-level junior representative rugby league and to verify and describe characteristics of x-Patch^{TM} recorded impacts via video analysis.

Study Design: Observational case series.

Methods: The x-Patch^{TM} was used on twenty-one adolescent players (thirteen forwards and eight backs) during a 2017 junior representative rugby league competition. Game-day footage, recorded by a trained videographer from a single camera, was synchronised with x-Patch^{TM} recorded timestamped events. Impacts were double verified by video review. Impact rates, playing characteristics, and gameplay situations were described.

Results: The x-Patch^{TM} recorded 624 impacts ≥20g between game start and finish, of which 564 (90.4%) were verified on video. Upon video review, 413 (73.2%) of all verified impacts ≥20g where determined to be direct head impacts. Direct head impacts ≥20g occurred at a rate of 5.2 impacts per game hour; 7.6 for forwards and 3.0 for backs (range = 0–18.2). A defender's arm directly impacting the head of the ball carrier was the most common event, accounting for 21.3% (n = 120) of all impacts, and 46.7% of all "hit-up" impacts. There were no medically diagnosed concussions during the competition.

Conclusion: The majority (90.4%) of head impacts ≥20g recorded by the x-Patch^{TM} sensor were verified by video. Double verification of direct head impacts in addition to cross-verification of sensor-recorded impacts using a secondary source such as synchronised video review can be used to ensure accuracy and validation of data.

Keywords: Head impacts, Rugby league, Wearable sensors, Accelerometer, Video review

Key Points

- There was a substantial number of false-positive high acceleration impacts recorded that occurred before, during, or after the games. Wearable instrumented technology has limitations as a primary data source and should be used in conjunction with video review.
- The vast majority of high acceleration impacts (≥20g) that occurred during game time were verified on video review.
- Careful time synchronisation of impact sensor recorded events and match video is vital to help cross-validation and to reduce over-estimation of an athlete’s direct head impact exposure.

Background

Rugby league carries a risk of concussion due to its high intensity and frequency of collisions [1]. Youth athletes may be more vulnerable to sustaining a concussion [2,3,4] and may also take longer to recover from a concussion than adult athletes [5,6,7,8]. Recently, various technology has been introduced to assist in the identification of head impacts and suspected concussions during athlete competitions. For instance, sideline video review [9,10], and to a lesser extent, impact sensors in helmeted and non-helmeted sports have been introduced to measure kinematic forces to the head [11,12].

Sideline video review has become increasingly common in professional sports for identifying head impact events and potential concussions. Recently, multiple experts from seven national and international professional sporting codes developed international consensus definitions of video signs of possible concussion, agreeing on six video signs: (i) lying motionless (for >2s); (ii) motor incoordination (e.g. losing balance); (iii) impact seizure; (iv) tonic posturing (involuntary sustained contraction of one or more limbs); (v) no protective action/floppy; and (vi) blank/vacant look [9]. The National Rugby League (NRL) has incorporated a Head Injury Assessment (HIA) process that uses sideline video review as a method to identify direct head impacts and potential signs of concussion in players. The identification of a player displaying potential signs of concussion evokes the HIA process, which includes mandatory immediate removal from play and subsequent assessment [13]. During the 2014 season, the incidence of suspected concussions based on the use of this process was 24.0 per 1000 NRL player game hours [13]. In the same season, the incidence of medically diagnosed concussions following the use of this process was 8.9 per 1000 player game hours [14].

Another proposed method for ascertaining whether a possible concussion occurred during gameplay has been measuring the kinematic responses of a player's head to impact forces through wearable sensor technology. The X2 x-Patch™ is an impact sensor designed for non-helmeted athletes that has been used in three previous rugby league studies in junior, women's, and semi-professional competitions [15,16,17]. Worn behind the ear, the x-Patch™ uses a triaxial gyroscope and accelerometer to calculate linear and angular accelerations experienced by the head during collisions [18]. Previous x-Patch™ studies in under 10-year-old rugby league [15] and under 9-year-old rugby union [19] reported on impact magnitudes comparable to studies on young adults. However, given that the x-Patch recorded impacts were not verified on video, the validity of these findings is questionable [20]. Some studies have examined helmeted impacts in 15 to 17-year-old athletes (e.g. American Football [21,22,23,24], Lacrosse [18]) using wearable sensors, but no studies have examined impacts in similarly aged rugby league players. Given that a direct head impact is more likely to result in a concussion than an indirect head impact [25], the relevance of player characteristics and gameplay situations to the relative risk of sustaining concussion may be an important consideration. The purpose of this study is to (i) determine the rate at which sensor-recorded impacts using the x-Patch™ are verified on video review of game footage, (ii) document the number of video verified direct head impacts that are not recorded on the sensors, and (iii) describe and compare playing characteristics and gameplay situations of video-verified direct and indirect impacts over a season of play in a squad of elite-level youth (under 16s) rugby league players.

Methods

Participants

A prospective cohort study was performed on a junior male representative rugby league team during the 2017 New South Wales (NSW) Rugby League Harold Matthews Competition. The Harold Matthews competition is an elite-level, state-based season of games for under 16-year-old male rugby league players. It forms one of the first stages of the elite-level pathway. The competition consists of 16 clubs from the NRL and Canterbury (NSW) Cup competitions. The Harold Matthews competition is played over 9 weeks, with the top five teams qualifying for the post-season (i.e. a 3-week finals series). From a squad of 22 adolescent players, 21 (age range: 15–16 years, mean = 15.5 years, SD = 0.5 years) including 13 forwards and 8 backs from one club participated in the study, with one player declining to participate. Written consent was obtained by a legal parent or guardian for each participating player, and verbal assent was obtained by each individual player. A rugby league team consists of 13 players (6 forwards and 7 backs) on the field at any one time with 4 interchange players. On average, data were collected from 13 participants per week (range: 9–15 players per week).

The research protocol was approved by the University of Newcastle Human Research Ethics Committee. The study was also endorsed by the participating club. The methods for data collection were identical to our previous study on a semi-professional men's rugby league team [17].

Measures

Impact Sensors

A total of 15 x-Patch^{TM} sensors (X2 Biosystems) were available and deployed at the beginning of the season. Each sensor contains a low-power, high-g triaxial accelerometer, and gyroscope that measures linear and angular accelerations and decelerations to provide 6 degrees of freedom kinematic head impact data. All players' sensors were attached to the skin covering the right mastoid process by an experienced member of the research team. Positioning of the sensor is crucial to ensure it is not activated by soft tissue muscles in the neck [26]. Each sensor was uniquely labelled and attached before the warm up using a double-sided adhesive patch. The x-Patch^{TM} is triggered when linear acceleration exceeds 10g and records data for 90ms after the trigger and 10ms before the trigger equalling one-tenth of a second of data (100ms) to its on-board memory. Once the sensor is removed, its stored data can be downloaded and analysed using the Injury Management Software (IMS; X2 Biosystems). Each recorded event is "timestamped" and a set of impact measures are recorded, including PLA, peak rotational acceleration (PRA), peak rotational velocity (PRV), and head impact location. In our study, a Head Impact (HI≥20g) was defined as an event recorded by the x-Patch^{TM} with a peak linear acceleration (PLA) ≥20g. Emphasis was placed on impacts ≥20g to avoid confusion with a large number of low-acceleration events, unlikely to result in deleterious neurophysiological change [17,27]. Brennan et al [28] observed that the mean PLA associated with concussion was 99g. PLA was utilised in this as previous research shows it has greater reliability and less variance than rotational measurements [20,29]. To remove low-acceleration events commonly associated with normal gameplay (e.g. sharp changing of directions, jumping, running) all video-verified impacts were filtered to only include HI≥20g as suggested in previous studies [17,27,30].

Sensors were collected from players after the game. All recorded impacts were reviewed and extracted from IMS, displayed in the form of a Microsoft Excel spreadsheet, and sorted into individual player cross-tabulations. Each sensor was then cleared of all impacts and charged in preparation for the following game.

Video Review and Synchronising with Sensors' Time Stamp

Each game was recorded with a single high-definition camera by a trained videographer. The video closely followed the play, including both the ball carrier and engaged defenders, and therefore captured competition-related collisions. The best possible vantage point was obtained on the midline of the field with close-up shots panning left and right to follow the play. Each game was reviewed from start to finish using QuickTime X (Apple Inc.) by one reviewer (LC). Video was synchronised with the timestamps of each sensor before the verification review was conducted. The first head impact seen on video review was checked against the HI≥20g after the game start time on the sensor's timestamp, the same synchronisation method used previously on collegiate Lacrosse athletes by Kindschi and colleagues [31]. Subsequent video-recorded impacts were then checked against timestamps at corresponding intervals. To synchronise the timestamp from the x-Patch™ with the video footage time, multiple impacts were reviewed on video and aligned to the sensor timestamp. Each potential video verified HI≥20g (VV-HI≥20g) was checked multiple times with both the timestamp and video to establish they were precisely synchronised before conducting the video verification process from start to finish of gameplay.

VV-HI≥20g were also classified by the game event or situation. Each VV-HI≥20g was deemed to be a "Hit-Up" (attacking player carrying the ball), "Tackle" (defending player attempting to stop the ball carrier), or "Off-The-Ball" incident (contact without the ball).

Triggered events ≥20g that did not correlate with a collision on video review were documented. Similarly, collisions on video review that involved a player with a working sensor attached and did not correspond to a triggered event were documented. For this study a “Direct VV-HI≥20g” was defined as a clearly observed physical head contact that corresponded with a HI≥20g, whereas an “Indirect VV-HI≥20 g” was a clearly observed body contact, excluding the head, that corresponded with a HI≥20g. VV-HI≥20g were then sorted into a number of sub-categories including the following: (i) direct (impact to head) vs. non-direct, (ii) number of tacklers involved (i.e. 1–4), (iii) point of impact on player with sensor (i.e. head, shoulder, chest, arm, waist and below), (iv) side of impact (i.e. right, left, front, back, top), (v) point of contact from opposition player (i.e. head, shoulder, chest, arm, waist and below), and (vi) wrestling impacts happening after first initial contact from tackle. A second reviewer (AG) then independently reviewed HI≥20g during game time that were *not verified on video*. The process of double verification of these “false-positive” impacts helped clarify the accuracy of each ‘impact’ included in the video verified data. Using the synchronised data set, the timestamps of non-verified HI≥20g were double-checked with the corresponding video time. Video for approximately 20s before and after the HI≥20g was reviewed with a focus on the relevant player. The results of this review process were then coded into categories (e.g. “HI≥20g not fully visualised in the available footage”, or “HI≥20g fully visualised with no contact identified”). All HI≥20g cases that were not verified as involving either a direct or indirect impact were excluded from the analyses. This double verification process was conducted independently by the two reviewers.

Statistical Analyses

Descriptive statistics for PLA and PRV of VV-HI≥20g were calculated and included frequencies, percentages, medians, and standard deviations. VV-HI≥20g per player game hours rates were calculated for all players and positions using the number of VV-HI≥20g divided by the number of game hours. The formula for calculating the impact rate is provided below.

$$\text{Impact Rate} = \frac{\sum \text{VV-HI}\geq 20\text{g}}{\sum \text{Player Game Hours}}$$

Percentages of video verified and non-verified HI≥20g were calculated to determine the validity of the x-Patch™ and to remove any "false positives" from the analysed data set. This was calculated as the number of VV-HI≥20g divided by the number of total recorded HI≥20g during gameplay, multiplied by one hundred. The formula for calculating percentage of verified impacts is provided below.

$$\%\ \text{Video Verified Impacts} = \frac{\sum \text{VV-HI}\geq 20\text{g}}{\sum \text{HI}\geq 20\text{g}} \times 100$$

Location accuracy of direct and indirect VV-HI≥20g was analysed and the accuracy percentage was calculated to show the agreement between the VV-HI≥20g impact location (i.e. front, back, side, top) estimated from the sensor data in the IMS and video review. Location accuracy percentages were calculated as the number of times the sensor-based and the video-based location estimates were in agreement divided by the total number of impacts per location on video review, multiplied by one hundred. The formula for location accuracy for VV-HI≥20g is provided below.

$$\text{Location Accuracy for VV-HI}\geq 20\text{g} = \frac{\sum \text{location agreement}}{\sum \text{total video locations}} \times 100$$

VV-HI≥20g data were reviewed for playing positions (i.e. forward versus back) and characteristics (i.e. attacking, defending, off-the-ball). An identical approach to our previous video verification study [17] for the analysis of this data was conducted. VV-HI≥20g incidence rates for forwards and backs were compared using an exploratory *t* test. Exploratory Mann-Whitney *U* tests compared impact magnitude (i.e. PLA, PRV) between video-verified/non-verified HI≥20g, direct/indirect VV-HI≥20g, first/second half VV-HI≥20g, and forward/back position VV-HI≥20g because these variables were not normally distributed. All analyses were performed using SPSS 23 (IBM Corp).

Results

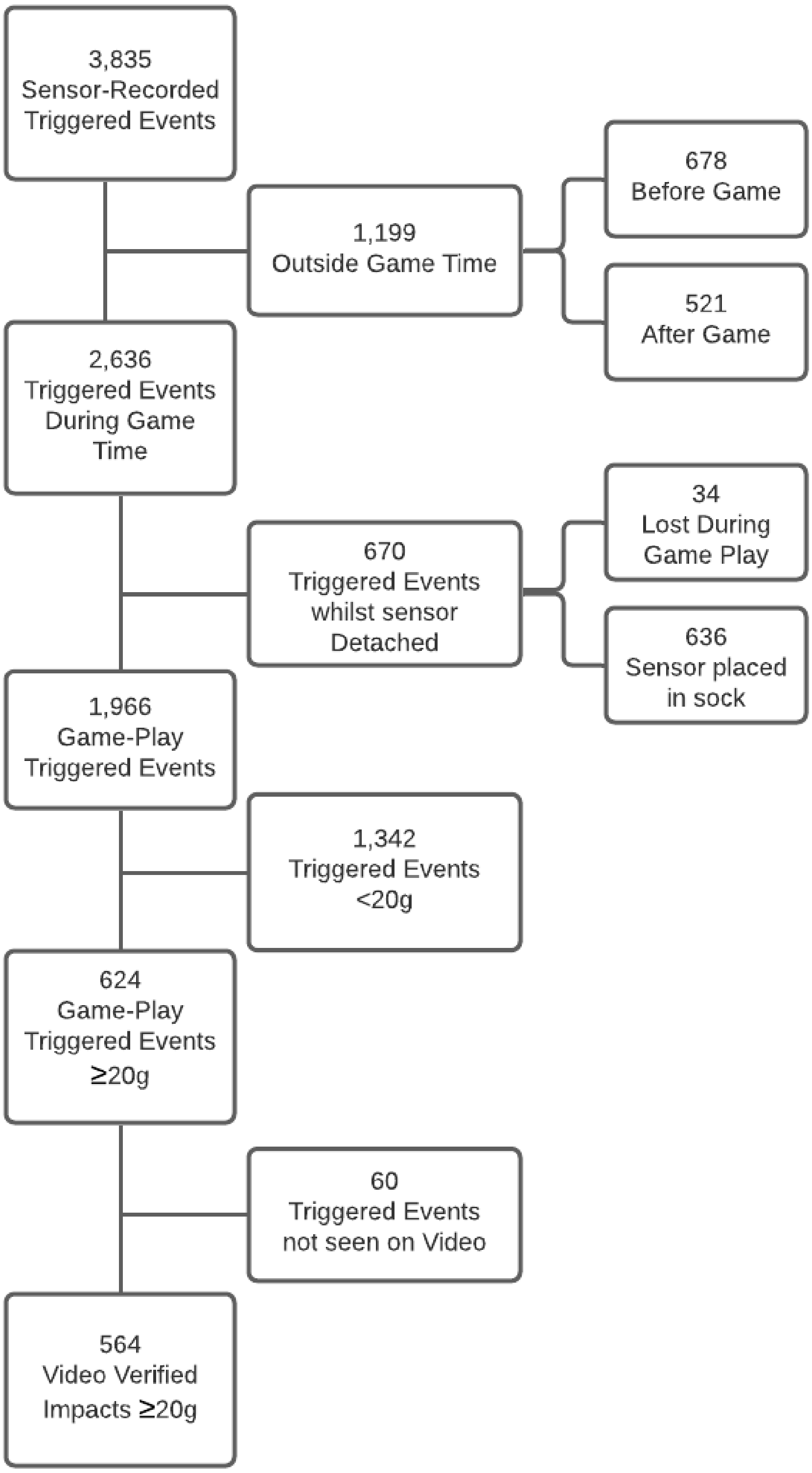
Game Hours and Sensor Recording

A total of 79.4 player game hours (4762 min) was recorded, with backs accounting for 52.1% (2479 min) and forwards accounting for 47.9% (2283 min) of the hours. Throughout the season, the number of available and working sensors was reduced to eleven due to deteriorating battery life (i.e. the sensor did not recharge), or the sensor was permanently lost during a game. The x-Patch^{TM} became detached 16 times throughout the season from eight different players (2 players once, 5 players twice, and 1 player 4 times), for a total of 456 min of lost data due to detached sensors for the season (backs: n = 4, total = 148 min, mean = 37 min, median = 33 min, SD = 11.11, range = 29–53; forwards: n = 12, total = 308, mean = 25.7 min, median = 28.5 min, SD = 9.94, range = 11–45). In addition, there was 121 min of game time lost due to 3 faulty sensors (all forwards).

Sensor Recorded Impacts

There were 3835 triggered events recorded by the x-Patch^{TM} with PLA ≥10g (see Fig. 1). Triggered events that could be interpreted as head impacts that occurred outside of game time (i.e. in warm up, cool-down, during application/removal of sensors) accounted for 1199 impacts (31.3%; 678 before game, 521 after game). On video review, 34 triggered events were removed due to occurring in the process of, or after, the sensor becoming detached in a tackle. A further 636 triggered events were removed due to two players placing the sensor in their sock after it became dislodged leaving a total of 1966 triggered events with PLA ≥10g during gameplay. From these triggered events, 1342 were <20g and therefore excluded which yielded a total of 624 triggered events ≥20g during gameplay (HI≥20g).

Fig. 1 Flow diagram of sensor recorded impacts and video verification



Video Verification of Sensor-Recorded Impacts

Of the 624 HI≥20g during gameplay, 564 (90.4%) were verified on video. The distribution of all x-Patch™ triggered events and VV-HI≥20g can be found in Fig. 2. From 564 VV-HI≥20g, 257 were as a result of a hit-up, 278 from a tackle, and 29 off-the-ball incidents. 413 (73.2%) were identified as direct head impacts and 151 (26.9%) as non-direct impacts occurring to either the shoulder, chest, arm, or waist. Of the 413 direct VV-HI≥20g, the tackler (defender) recorded 204 (49.4%), the ball carrier (attacker) recorded 186 (45.0%), while 23 were recorded during off-the-ball incidents (5.6%; incidental contact $n = 4$; melee/scuffle or fighting $n = 1$; contact celebrating tries $n = 10$; contact celebrating penalty $n = 1$; contact packing scrums $n = 5$; clutching at own head after tackle $n = 2$). Direct VV-HI≥20g (as determined by video review) had a greater PLA compared to indirect VV-HI≥20g [direct $n = 413$, mean = 37.3, median = 31.3, SD = 17.5, range 20–113.3; indirect $n = 151$, mean = 25.5, median = 24.0, SD = 5.4, range 20–45.7; U = 15,728.00, $p < .001$; Cohen's $d = 0.83$] as well as greater PRV compared to indirect VV-HI≥20g [direct $n = 413$, mean = 29.9, median = 28.5, SD = 11.3, range 6.8-56.6; indirect $n = 151$, mean= 24.8, median = 23.4, SD = 8.7, range 6.2–54.9; $U = 23{,}162.00$, $p < .001$; $d = 0.48$].

Figure 3 provides a comparison of the peak linear acceleration and peak rotational velocity between all direct and indirect VV-HI≥20g. The individual player data by position, playing time, video-verified impacts, and VV-HI≥20g per game hour are provided in Table 1.

Fig. 2 Distribution of all x-Patch™ triggered events and VV-HI≥20g

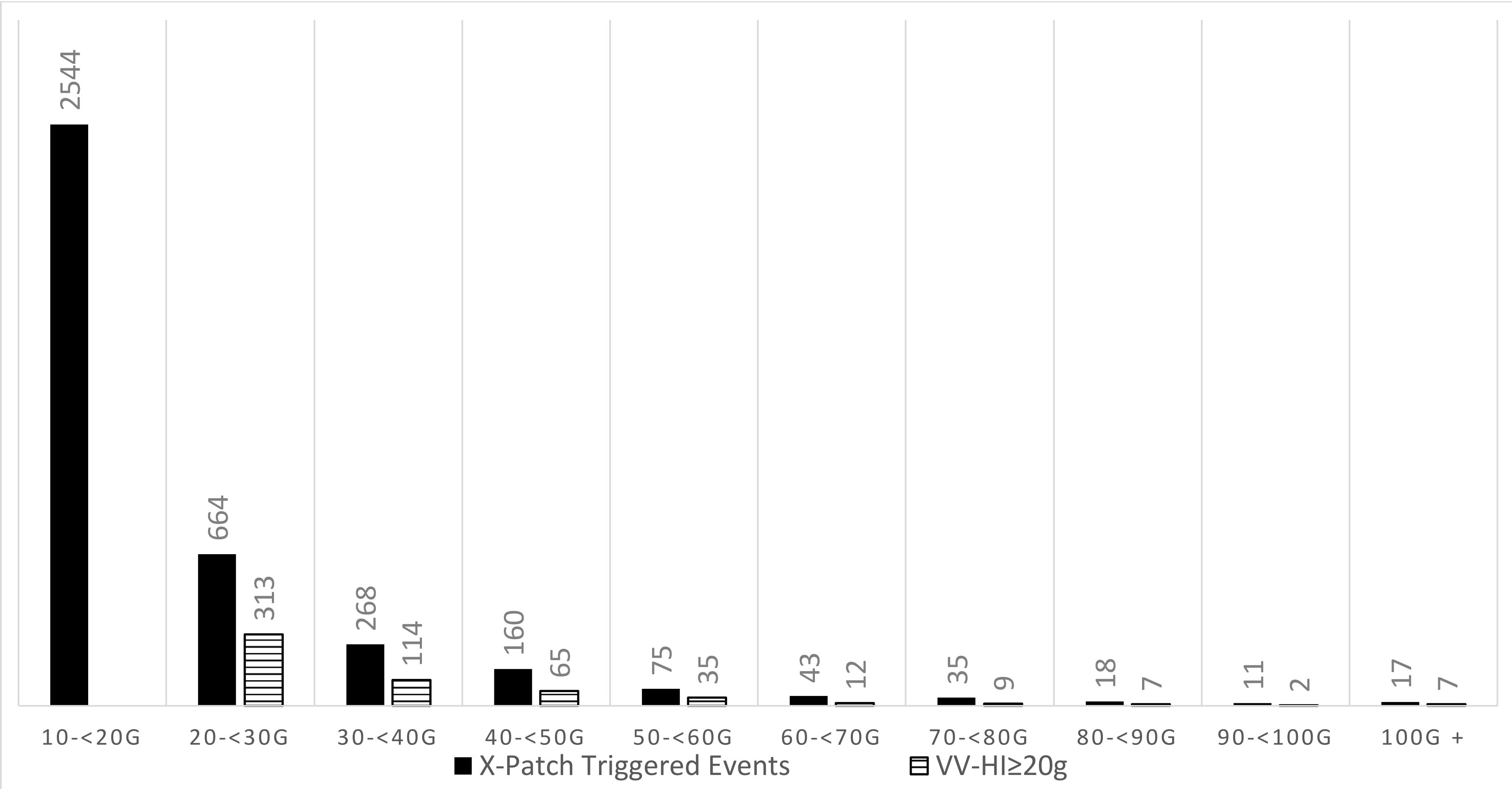
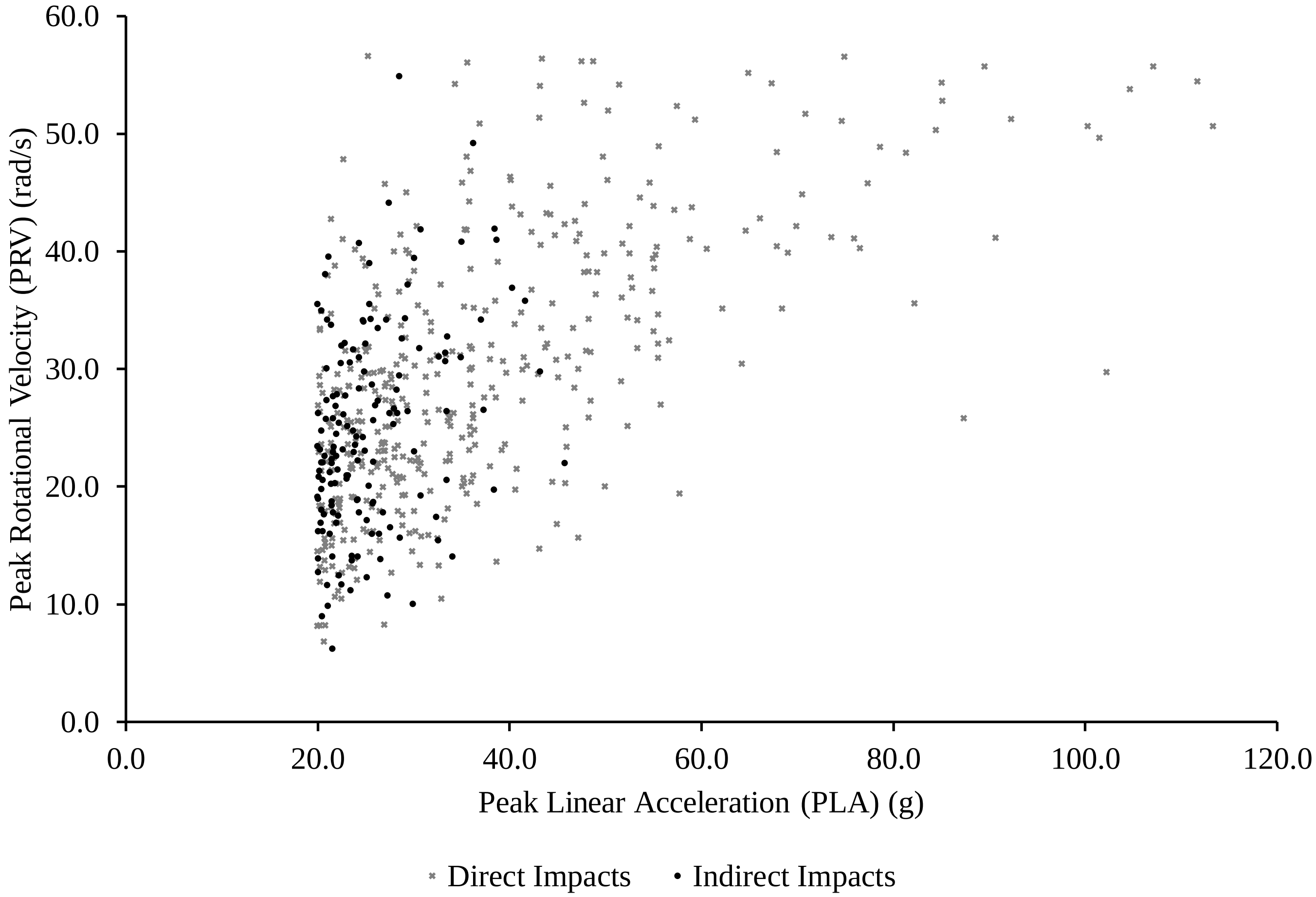


Fig. 3 Scatterplot of Video Verified Direct and Indirect Impacts ≥20g Recorded by the x-Patch™



Note: Direct impacts are to the head and indirect impacts are to the body.

Table 1 Cross-tabulation of Frequency of Verified In-Game Impacts ≥20g Measured by the x-Patch™

			All x-Patch™ Recorded Impacts During Game Time				x-Patch™ Recorded Direct Impacts	
	Playing Position	Player Time in Game (Mins)	Sensor-Recorded In-Game Impacts	Video Verified Game Impacts	Percentage of Impacts Verified (%)	Video Verified Impacts per Game Hour	Video Verified Direct Impacts	Video Verified Direct Impacts per Game Hour
Player 1	Back	211	17	16	94.1	4.5	12	3.4
Player 2	Back	337	22	22	100	3.9	17	3.0
Player 3	Back	490	46	44	95.7	5.4	30	3.7
Player 4	Back	463	36	36	100	4.7	24	3.1
Player 5	Back	300	14	14	100	2.8	9	1.8
Player 6	Back	390	15	15	100	2.3	10	1.5
	Forward	30	2	2	100	4	1	2
Player 7	Forward	259	26	25	96.2	5.8	14	3.2
Player 8	Forward	192	39	35	89.7	10.9	22	6.9
Player 9	Forward	204	67	56	83.6	16.5	44	12.9
Player 10	Forward	398	37	37	100	5.6	31	4.7
Player 11	Forward	272	25	25	100	5.5	20	4.4
Player 12	Forward	247	63	63	100	15.3	45	10.9
Player 13	Back	87	12	11	91.7	7.6	8	5.5
	Forward	63	10	8	80	7.6	7	6.7
Player 14	Forward	118	24	16	66.7	8.1	13	6.6
Player 15	Forward	91	30	26	86.7	17.1	20	13.2
Player 16	Forward	185	62	47	75.8	15.2	37	12
Player 17	Back	180	20	18	90	6	12	4
Player 18	Forward	36	9	8	88.9	13.3	3	5
Player 19	Forward	72	12	11	91.7	9.2	9	7.5
Player 20	Forward	56	26	21	80.8	22.5	17	18.2
Player 21	Back	21	1	0	0	0	0	0
	Forward	60	9	8	88.9	8	7	7
Total		4,762	624	564	90.4	7.1	413	5.2

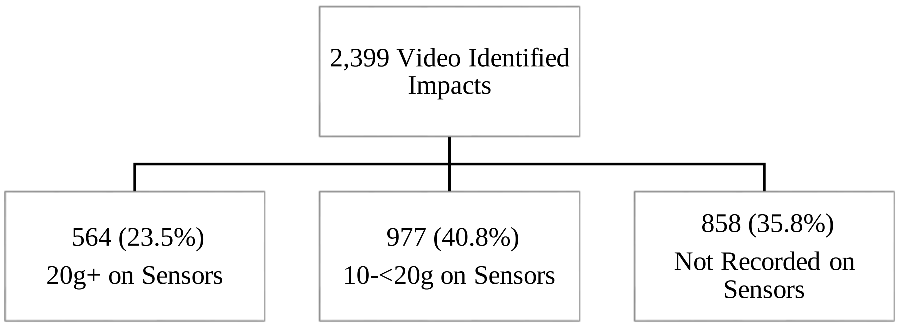
Note. Season Totals. Players 6, 13 & 21 played in both forward and back positions during the season. Sensor recorded impacts were ≥20gs.

Impacts Seen on Video and Not Recorded on the Sensors

There were 858 video observed impacts, including 28 direct head impacts, that did not result in any triggered event from the x

x-Patch^{TM}, either because the sensors did not activate (despite other impacts being recorded on those sensors in close temporal proximity) or because the impact did not reach the 10g threshold (see Fig. 4).

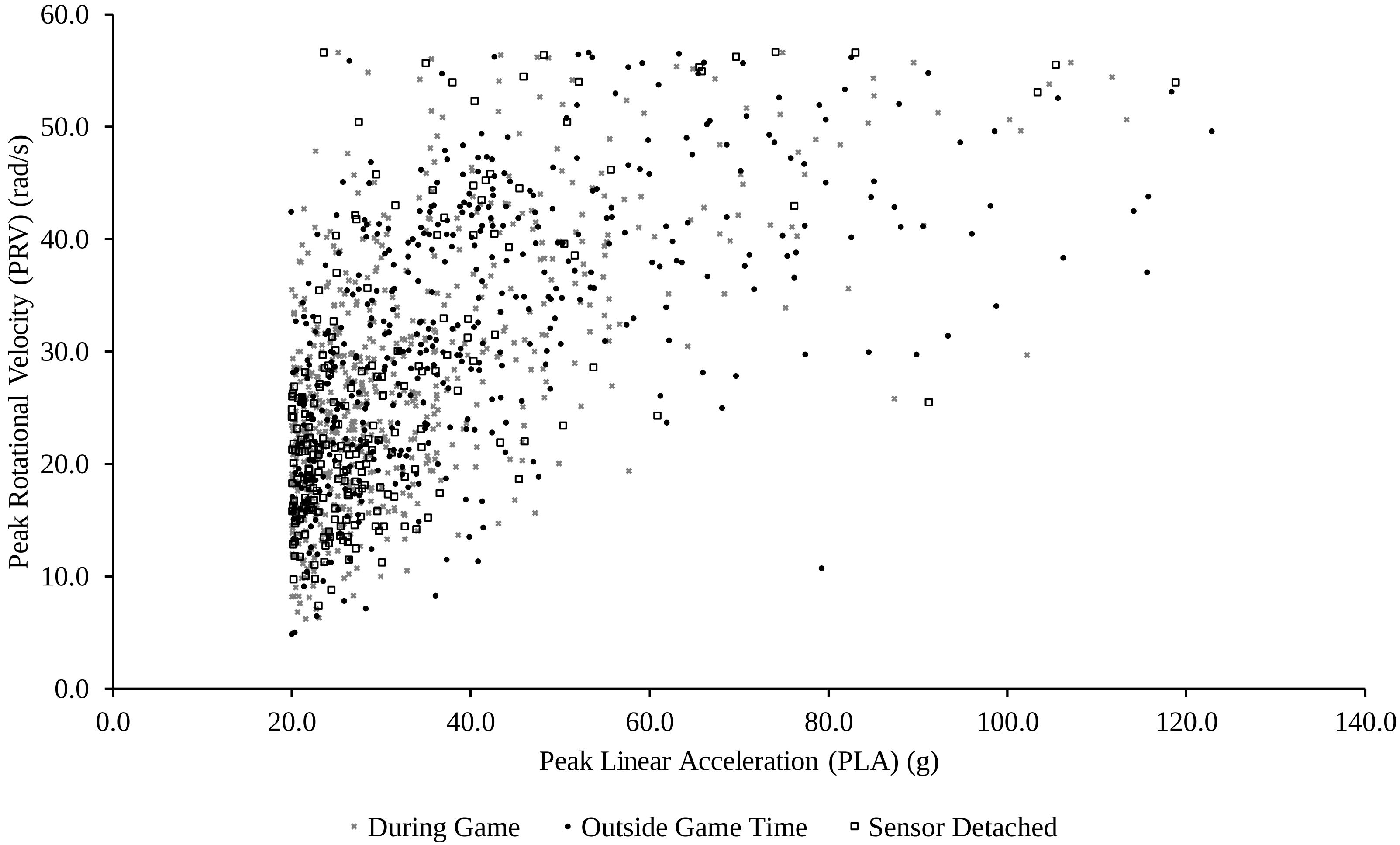
Fig. 4 Flow diagram showing video verified impacts



Sensor Recorded Impacts Not Verified on Video

There were 1199 triggered events that occurred before or after the game which were removed from the analysed data (Fig. 1). There were 506 triggered events registered as ≥20g that were not seen on video, and of those 185 occurred before the game (36.6%, presumably during warm up), 60 occurred during the game (11.9%), and 261 occurred after the game (51.6%). Individual impacts during the game, outside game time, and while the sensor was detached are illustrated in Fig. 5.

Fig. 5 Scatterplot of all impacts ≥20g recorded by the x-Patch™



Note: Sensor detached refers to impacts recorded after the sensor has been visualized dislodging on video review (including players seen placing the sensor in their sock and continuing to play).

A total of 60 HI≥20g that occurred during game time were not verified on video review. Of these, 33 HI≥20g were recorded when the player was on the bench, 15 were not visualised (including 12 impacts while the player was not involved or was "behind" the play and three impacts when the game was halted after the awarding of a penalty), one was partially visualised on video but was indeterminant, and 11 recorded impacts had complete visualisation but with no identified contact (including seven during a sharp change of direction from the player, three during change of speed while running, and one with no visible correlate). In all of these instances, there was clearly no contact from another player. Each of these HI≥20g was verified by two reviewers to confirm them as "false-positive" impacts. There was no significant difference in the PLA of VV-HI≥20g versus false-positive HI≥20g [verified n = 564, mean=34.1g, median = 28.4g, SD = 16.1, range = 20.0–113.3g; non-verified n = 60, mean = 30.9g, median = 26.1g, SD = 13.3, range = 20.0–76.6g; U = 14,706.00, p = .10; d = 0.20] but a difference in PRV [verified mean = 28.5rad/s, median = 26.9rad/s, SD = 10.9, range = 6.2–56.6rad/s; non-verified mean = 25.2rad/s, median = 22.4rad/s, SD = 13.0, range = 6.3–55.4rad/s; U = 13,727.00, p = .02, d = 0.30].

Situational Characteristics of Video Verified and Sensor Recorded Impacts

Of the 413 direct VV-HI≥20g, players sustained an average of 5.2 direct VV-HI≥20g per hour of gameplay, with a slightly higher rate of direct VV-HI≥20g during the second half of the game [first half 4.6 impacts/h, n = 192; second half 5.8 impacts/h, n = 221]. The magnitude of these direct VV-HI≥20g did not statistically differ between the first and second half (PLA: U = 20,211.00, p = .41; PRV: U = 21,088.00, p = .92). Forwards had a higher rate of direct VV-HI≥20g than backs [forwards M = 8.08 impacts/h, SD = 4.46; backs M = 2.90 impacts/h, SD = 1.60; $t(22)$ = 7.58 p = .001, d = 1.29]. However, the intensity of direct VV-

HI≥20g did not statistically differ between forwards and backs (PLA: $U = 17{,}047.00$, $p = .53$; PRV: $U = 17{,}656.00$, $p = .93$).

The most common event that caused a VV-HI≥20g was from a defender's arm directly impacting the head of a ball carrier ($n = 120$). This type of gameplay accounted for 21.3% of all VV-HI≥20g and 46.7% of all hit-up VV-HI≥20g. The most common event associated with a VV-HI≥20g for a tackler was an attacker's arm ($n = 60$) or waist ($n = 60$) directly impacting the head of the tackler. Each of these accounted for 10.6% of all VV-HI≥20g and 21.6% of tackler VV-HI≥20g. Contact with the playing surface accounted for 44 VV-HI≥20g (7.8%; hit-up $n = 32$, tackle $n = 9$, off-the-ball $n = 3$). Of the 151 indirect VV-HI≥20g, a ball carrier's shoulder impacting with a defender's shoulder (11.9%, $n = 18$, 3.2% of all impacts) or the defender's chest impacting a ball carrier's shoulder (10.6%, $n = 16$, 2.9% of all impacts) were the most common. A detailed overview of all VV-HI≥20g for a hit-up, tackle, and off-the-ball events is provided in Table 2.

Table 2 Sensor Recorded and Video Verified Impact Locations ≥20g

Point of Impact	Impact from Opposition: Head	Shoulder	Chest	Arm	Waist	Leg/knee	Ground	Total
Head	13[a] (4,7,2)	64[b] (26,37,1)	34[c] (12,22,0)	199[d] (120,60,19)	66[e] (5,60,1)	26[f] (13,13,0)	11 (6,5,0)	413 (186,204,23)
Shoulder	0 (0,0,0)	30 (11,18,1)	29 (16,13,0)	2 (2,0,0)	13 (1,12,0)	0 (0,0,0)	10 (8,1,1)	84 (38,44,2)
Chest	0 (0,0,0)	26 (10,16,0)	10 (2,8,0)	5[g] (0,3,2)	0 (0,0,0)	0 (0,0,0)	18 (14,2,2)	59 (26,29,4)
Arm	0 (0,0,0)	0 (0,0,0)	0 (0,0,0)	0 (0,0,0)	0 (0,0,0)	0 (0,0,0)	1 (1,0,0)	1 (1,0,0)
Waist	0 (0,0,0)	3 (3,0,0)	0 (0,0,0)	0 (0,0,0)	0 (0,0,0)	0 (0,0,0)	4 (3,1,0)	7 (6,1,0)
Total	13 (4,7,2)	123 (50,71,2)	73 (30,43,0)	206 (122,63,21)	79 (6,72,1)	26 (13,13,0)	44 (32,9,3)	564 (257,278,29)

Note. Data in the parentheses are for a hit-up, tackle and off-the-ball incident, as follows: (hit-up, tackle, off-the-ball)

[a] 4 impacts from teammate’s head (3 tackle, 1 off-the-ball)

[b] 7 impacts from teammate’s shoulder (tackle), 1 impact from player’s own shoulder (hit-up)

[c] 6 impacts from teammate’s chest (6 tackle)

[d] 32 impacts from teammate’s arm (20 tackle, 12 off-the-ball), 2 impacts from player’s own arm (2 off-the-ball)

[e] 5 impacts from teammate’s waist (4 tackle, 1 off-the-ball)

[f] 2 impacts from teammate’s leg/knee (2 tackle)

[g] 1 impacts from teammate’s arm (off-the-ball)

Direction of Sensor Recorded and direct VV-HI≥20g

When looking at the location of all direct VV-HI≥20g (*n* = 413) via the IMS, most occurred to the front (*n* = 198; 47.9%), followed by the side (*n* = 111; 26.9%), back (*n* = 83; 20.1%), and top (*n* = 21; 5.1%) of the head. When examining the location via video review, we found most direct VV-HI≥20g occurred to the side (*n* = 357, 86.4%) with fewer to the front (*n* = 14, 3.4%), back (*n* = 34, 8.2%), and top (*n* = 8, 1.9%) of the head. The location of direct VV-HI≥20g corresponded in only 24.9% of cases with the video review [42.9% (*n* = 6) to the front of the head, 25.2% (*n* = 90) to the side, 17.6% (*n* = 6) to the back, and 12.5% (*n* = 1) to the top]. The sensor-derived impact location was poorly correlated with side-on direct head impacts visualised on video, and as such overestimated VV-HI≥20g in all other directions, particularly front-on impacts. A detailed description of the location accuracy for direct and indirect VV-HI≥20g is provided in Table 3.

Table 3 Video Verified Impacts: Location Accuracy of Direct and Indirect Impacts ≥20g

	Total				Direct Impact				Indirect Impact			
	x-Patch™ (n)	Video (n)	Agreement (n)	Accuracy (%)	x-Patch™ (n)	Video (n)	Agreement (n)	Accuracy (%)	x-Patch™ (n)	Video (n)	Agreement (n)	Accuracy (%)
Front	269	68	35	51.5	198	14	6	42.9	71	54	29	53.7
Side	150	447	118	26.4	111	357	90	25.2	39	90	28	31.1
Back	116	41	9	22.0	83	34	6	17.6	33	7	3	42.9
Top	29	8	1	12.5	21	8	1	12.5	8	0	0	0
Total	564	564	163	28.9	413	413	103	24.9	151	151	60	39.7

Tackles and Secondary Impacts

Secondary impacts during a tackle (i.e. impacts after the initial contact in the same tackle event) accounted for 46.1% (*n* = 260) of total VV-HI≥20g and 53.5% (*n* = 221) of all direct VV-HI≥20g. For 260 secondary impacts, 16.2% (*n* = 42) were accompanied by a VV-HI≥20g. There were 456 tackles that resulted in the 535 VV-HI≥20g, excluding impacts that occurred "off the ball." For 388 tackles there was one impact recorded, for 60 there were two impacts recorded, for 7 there were three impacts recorded, and for 1 there were six impacts recorded. There were an additional 27 incidents occurring off the ball that resulted in 29 VV-HI≥20g (25 with one impact recorded and 2 with two impacts). The hit-up was a play that accounted for approximately 47.1% (*n* = 215) of all x-Patch™ recorded events. Of the hit-up plays, the forward positions accounted for 62.8% (*n* = 135) of those impacts, while the back positions accounted for approximately 37.2% (*n* = 80) of impacts. The tackle accounted for approximately 52.9% (*n* = 241) of all x-Patch™ recorded events. Of the tackles, the forward positions accounted for 73% (*n* = 175) of those impacts, while the back positions accounted for approximately 27% (*n* = 66) of impacts.

Discussion

This study is the first to analyse video and verify x-Patch™ recorded data in elite youth rugby league players. VV-HI≥20g accounted for 90.4% of all HI≥20g during game time, revealing a high rate of agreement, similar to rates previously recorded in men's semi-professional rugby league [17]. Cross-verification with a secondary source, such as video review, is highly recommended to reduce false-positive readings that may inflate players' cumulative and average PLAs across a season. Of particular importance is the risk for fundamentally misinterpreting the highest acceleration readings, because those could be falsely attributed to high energy head impacts. Of the 45 impacts recorded as 80gs or greater, only 35.6% occurred during the game, while 55.6% were outside game time, and 8.9% were recorded while the sensor was known to be detached (Fig. 5). When viewing video footage during one of our prior studies, we saw one example when six 40g or higher "head impacts" (ranging from 40.6 to 58.8g) were recorded after a game when two players were shaking hands and one player tapped the side of the other players head, during the handshake, presumably directly on the sensor [17].

Upon video review, we discovered not all recorded "head impacts" occurred as a result of a direct impact to the head. We recorded 5.2 direct VV-HI≥20g per game hour which is similar to that recorded previously in men's semi-professional rugby (6.0 direct VV-HI≥20g/h) [17]. Although the majority of VV-HI≥20g occurred as a result of a direct force to the head (73.2%), the x-Patch™ recorded impacts confirmed by video to be caused by an impulsive force to the head after an impact elsewhere on the body (i.e. chest/torso, shoulder, arm, etc.). The rate of direct VV-HI≥20g was not significantly different between the first and second half, but showed a greater exposure experienced by forwards when compared to backs, consistent with previous literature [17,32,33] (Table 4). There was poor agreement in the location and direction of VV-HI≥20g between the x-Patch™ and video review. This is consistent with in vivo laboratory findings which found skin-mounted sensors showed large measurement errors, with acceleration peaks in different directions from the same impacts recorded with mouthguard-based sensors [26]. For direct VV-HI≥20g, the x-Patch™ accurately recorded the location in 24.9% (*n* = 103) of impacts, see Table 3. Previously, Kuo and colleagues, using a similar tri-axial linear accelerometer embedded into a mouthguard, reported similarly poor rates of agreement between sensor-recorded and video-identified impacts (37.3%), with impact locations that did not match the visualised head kinematics [34].

Table 4 Frequency of Video Verified Direct Head Impacts by Game Time and Playing Position

		Sensor Recorded and Video Verified ≥20g		Verified Direct Head Impacts ≥20g	
	Playing hours (min)	Game impacts (n)	Impacts per game hour (n)	Game impacts (n)	Impacts per game hour (n)
1st Half	41.3 (2,479)	271	6.6	192	4.6
2nd Half	38.1 (2,283)	293	7.7	221	5.8
Forwards	38.1 (2,283)	388	10.2	291	7.6
Backs	41.3 (2,479)	176	4.3	122	3.0
Total Sample	79.4 (4,762)	564	7.1	413	5.2

Note. The total number of impacts by playing positions (forwards/backs) was divided by the total minutes played by each playing position.

It is important that when sensor data are collected, they are closely analysed because there is potential for gross over-estimation of head impacts if not carefully processed to remove triggered events outside of gameplay (Fig. 5) [17,18]. Of all triggered events ≥20g (*n* = 1,291), only approximately half (*n* = 624, 48.3%) occurred during the game, with the majority of impacts occurring either before or after the game or after a sensor had become detached from the head (Fig. 4). Upon video review, there were multiple triggered events (*n* = 22) after the sensor was seen detaching from a player, presumably from the sensor hitting the ground after falling or players stepping on it during the game. On two occasions, after the x-Patch™ became dislodged, the players can be clearly visualised placing the sensor in their sock until the conclusion of the game, leading to a large number of triggered events ≥20g (*n* = 199) being recorded from running.

In this study, we employed a video verification approach with two reviewers independently reviewing 60 HI≥20g that occurred during game time that were not verified by video. This was used for quality assurance to verify false-positive readings so that they could be confidently removed from head impact exposure data prior to analysis. Interestingly, upon close review of non-verified impacts, we discovered 33 impacts that occurred while the player was on the sideline. It is unclear how or why these impacts were recorded on the sensors because there was no available video of players on the sidelines. It is possible that these impacts occurred while players were preparing to enter the game by simulating tackles. Previously Cortes and colleagues [18], in a review of impacts in collegiate lacrosse, reported that 99 impacts ≥20g occurred on the sideline. This suggests that a secondary source, such as video review, is important when trying to quantify in-game recorded head impacts to ensure reported impacts occurred while the player was involved in the game. If the non-game data is not removed, it would artificially inflate the number of head impacts a player sustains. There were also a number of clear head impacts seen on video review that did not register on the sensor, consistent with previous x-Patch™ studies [20,35]. There were a total of 2399 video-identified impacts to the head or body. Of these, the authors of this study visualised 858 (35.8%) impact events on video review that were either not recorded at all by the sensor, or that registered as less than 10g, of which there were many observable direct head impacts (Fig. 2). The exact number of impacts is difficult to determine and may be higher because this number captures the number of events (e.g. tackles), and multiple impacts may have occurred in each event. We also found a large number of impacts were secondary impacts during tackle events that occurred after the initial contact with 46.3% of all verified impacts coming after the initial impact was seen on video. Of these secondary impacts, 83.8% occurred after the primary impact was either not recorded by the sensor or registered under the 20g threshold. Having multiple impacts in tackle events makes it difficult to determine exactly how many "larger" impacts identifiable on video review were not registered by the x-Patch™.

Limitations

This study consisted of a relatively small sample size, and no player played all games. Due to faulty equipment at the end of the season, the number of working sensors was less than the number of participating players in each game. Because of this, sensors were given to players likely to play more minutes throughout the game to maximise data collection. Further, due to time and personnel constraints, training sessions and two games throughout the season were unable to be staffed by research personnel; these data underrepresent the total accumulation of head impacts over the course of a full season. Additionally, our statistical analyses (i.e. *t* tests and Mann-Whitney *U* tests) were exploratory and should be replicated in larger, more representative samples. Similar to our previous study [17], false-negative incidences only included the initial impact as a single "missed" impact when there likely were more subsequent, or secondary, impacts also not registered by the sensor. Although we double verified each false-positive impact to ensure accuracy, all other impacts were coded by a single researcher creating a possibility of some impacts being missed due to human error. This study utilised one high-definition sideline video camera that panned across the entire field which limits the ability to accurately verify impacts and signs of concussion. Some impacts may be obstructed from view by another player, and thus, the exact location of some impacts may be inaccurate. Research studies on professional sports with multiple camera angles may be more accurate in analysing video signs of concussion and determining location of verified impacts. Critically, the process for synchronising, and interpreting, the video and x-Patch^{TM} data in a sport where continuous impacts are present is challenging. Given the volume of impact data collected from the x-Patch^{TM} when no apparent contact was observed (i.e. high sampling rate of the x-Patch^{TM} in the absence of verified impact), in combination with a sport that has a high frequency of body contact, it seems likely that the sensor is recording triggered events that are not actually impacts to the head or body [20,29].

Conclusion

The findings from this study are consistent with previous research, highlighting the importance of using video review as the primary source of information on head impact and supplementing that with x-Patch^{TM} recorded data. That is, the x-Patch^{TM} has serious limitations as a primary data source [17,18,20,27]. The current study identified similar high rates of false-positive direct head impacts recorded by the wearable sensors in junior representative rugby league as were previously described in semi-professional men's rugby league, Australian Football, and collegiate lacrosse respectively. Although there is potential for impact sensors to play an assistive role to medical staff, more research is needed to ensure the accuracy of data collected and to establish their usefulness for injury surveillance. With ongoing improvements in methodology and technology, future impact sensors might provide important information for junior or amateur sports in recording player exposure rates and differentiating between incidental movements and actual collisions.

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Chapter 4 – Discussion & Conclusion

4.1 – General Discussion

The purpose of this study was to utilise video review as a secondary source to verify and analyse x-Patch™ recorded head impacts in rugby league. Both studies focused on determining the reliability of sensor recorded data, describing playing characteristics and game-play situations of video-verified impacts and reporting direct head impact exposure rates in men's semi-professional and elite-level youth competitions. Current rugby league literature reporting sensor recorded head impact exposure has focused on junior and adult female competitions, without the use of video to verify recorded impacts (King, Hume, et al., 2017; King et al., 2018). Both of the previous rugby league studies reported on impacts ≥10g. For the purpose of this thesis, similar to criteria applied in previous studies (Caswell et al., 2017; McCuen et al., 2015), impacts <20g were removed as these low acceleration events are commonly associated with physical activities of game play and unlikely to result in deleterious neurophysiological changes.

There were similarly high rates of agreement between video-verified and sensor recorded game play impacts ≥20g in both men's semi-professional (94%) and elite-level youth (90%) rugby league. In both studies there were a large number of sensor recorded impacts that occurred outside of game time or whilst the sensor had become visibly dislodged form the player during the game, including incidents where the player collected the sensor and placed it in their sock where it continued to record impacts from running for the remainder of the game. In the first study, video footage immediately post-match revealed six high acceleration impacts, ranging from 40.6g to 56.8g, from a player shaking hands with opposition player where the sensor appeared to be tapped directly from the hand of another player. The second study in this thesis also revealed that of 45 impacts recorded ≥80g, only 35.6% occurred during game play. There were also a number of triggered events ≥20g that occurred during the game that did not correlate with an impact on video review, with many whilst the player was resting on the sideline. There were also a number of clear head impacts on video review that did not cause triggered event ≥10g. The use of a secondary source, such as video review, to verify x-Patch™ recorded impacts is extremely important when analysing total head impact exposure as failure to remove 'false-positive' impacts that do not occur as a result of game play may inflate player's cumulative and average head impact exposures across as season.

During the first study there were a total of six diagnosed concussions in players wearing the x-Patch™ with a large, statistically significant difference between PLA of concussive vs. non-concussive impacts. There were also a large number of impacts across both studies with a higher recorded PLA and no accompanying video identifiable signs of concussion or medically diagnosed concussion highlighting again that at this stage the x-Patch™ should not be used to help diagnose concussion. The second study had no medically diagnosed concussions, however during the video analysis there were many tackle events with video identifiable signs of concussion that would potentially have resulted in a HIA at the professional level (Davis et al., 2019a). Unfortunately immediate sideline video review of incidents looking for signs of concussion is not readily available in many non-professional competitions due to cost and trained medical personnel constraints. Future large scale studies utilising wearable impact sensor technology with concussive injuries is needed to determine if there is a use for this technology to aid clinicians with the identification and diagnosis of potential concussive injury.

4.2 - Limitations

Both studies in this thesis contained a relatively small sample size due to a limited number of working sensors, which decreased over time, and player consent with not everyone agreeing to partake. There are seventeen players on any one team, including bench players, that could be monitored however the first study had only eight participants with twenty-one participating in the second study. As the study progressed the number of available working sensors was decreased due to losing them on the field post game, faulty equipment and reduced battery life. Once number of working sensors became less than the participating players, priority was given to players likely to play more minutes to maximise data collection. The cost of the sensors and the potential need to continue replacing lost and faulty sensors provides a challenge for the utilisation of the x-Patch™ outside of a professional setting.

The utilisation of a single high-definition camera positioned mid-field to pan across the entire field meant there was only one available camera angle to analyse collisions and tackle events. Often the view of head impacts was obscured by other players in the tackle, players not involved in the tackle in the line of sight of the camera and also, on occasions, spectators standing up and walking in frame. Whilst the style of play in rugby league and the close proximity of all field players likely to be involved in collisions allowed for almost every player to be visualised in one shot panning left to right there was one occasion where the videographer did not follow play quick enough and missed a tackle event. This lead to a potential head impact having to be excluded from the data set as it could not be accurately verified by video. Across studies there was also a difference in the quality of video recordings with the elite-level youth competition often played in larger stadiums than the suburban grounds common in semi-professional local competitions. The larger stadiums allowed the videographer to have a higher vantage point which lead to a clearer view of tackle events with less obstructions. Whilst not possible in the current study due for financial and personnel reasons, future research studies in professional sports would benefit from having multiple camera angles and high quality slow motion viewing to increase the accuracy in determining the characteristics of head impacts and identifying video signs of possible concussion.

All of the video analysis and coding of impacts was done by myself and as such it is possible some head impacts were missed or coded incorrectly. The second study utilised a second reviewer to double verify each ‘false-positive’ impact, that is every sensor recorded impact ≥20g that was not seen on video review. This was to ensure the accuracy of these reported ‘false-positive’ impacts but this was not possible for every sensor recorded impact due to the large volume of data collected. Both studies reported on ‘false-negative’ impacts where there was a visible head impact on video review but no accompanying sensor recorded impact ≥10g. Many of the verified tackle events contained multiple separate sensor recorded head impacts but each ‘false-negative’ was coded as a single event meaning there was more than likely underestimation of ‘false-negative’ impacts in both studies. Whilst it is entirely possible that the force applied to the head in these tackle events was not great enough to trigger the 10g threshold of the sensors, upon video review many of these impacts were clear head impacts and appeared to have more force than a number of other triggered events.

4.3 - Conclusion

This thesis contains the first two studies to utilise video review to verify sensor recorded head impacts in rugby league. The first study found that video review was beneficial in verifying these sensor recorded impacts and could help describe game play characteristics and mechanisms of head impacts. The second study elaborated on this and highlighted the need for video review to be the primary source of identifying head impacts and supplemented with x-Patch^{TM} recorded data. The x-Patch^{TM} was shown to have serious limitations as a primary data source if used as the only measure of head impact exposure as it could grossly overestimate the magnitude of impacts received by each player. The adhesive requirements of the x-Patch^{TM} also led to lost data from exposed sensors falling off with contact. Alternative non-helmeted sensor designs, such as mouthguards, may help alleviate this issue and maximise data collection in future research projects. Whilst there is a role for impact sensors in recognition and analysis of head impacts more research is needed to be done to increase the accuracy and validity of these devices. Advancements in technology and improved methodology with large scale research studies could help impact sensors become useful in the detection of head impacts at all levels of sport. Future research into sport-related concussion should focus on video analysis of tackle events with impact sensors having the potential to help quantify the presence of a head impact in the case where video is not available or there is an obstructed view of tackle events, particularly below the professional level.

This thesis has contributed to the sport-related concussion literature in rugby league by combing the use of impact sensors and video analysis. The limitations of wearable impact sensor devices has been described and the need of a secondary source such as video review to verify these impacts has been highlighted. Future research projects should focus on video review as the primary method of identifying head impact exposure with advancements in technology needed to make impact sensors a more reliable source of data collection.

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